NWC TP 6827

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Geothermal Potential of Marine Corps Air Station, Yuma, Arizona, and the Western Portion of Luke-Williams Gunnery Range

by
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JANUARY 1988

NAVAL WEAPONS CENTER
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Naval Weapons Center

FOREWORD

The Geothermal Program Office (GEOPROFF) at the Naval Weapons Center (NWC), China Lake, California, was tasked by the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California, to perform a geothermal resource exploration program at the U.S. Marine Corps Air Station, Yuma, Arizona, and vicinity. The purpose of the program was to provide NCEL and the Marine Corps with information on the geothermal potential of the site.

The work was performed during 1984 and 1986 under Project No. R0829, Task No. R0829.

This report has been reviewed for technical accuracy by C. F. Austin and J. A. Whelan.

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Released for publication by
G. R. SCHIEFER
Technical Director

NWC Technical Publication 6827

Published by. . . . . Technical Information Department
Collation . . . . Cover, 30 leaves
First printing . . . . 145 copies

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

AD-A197 279

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY 2b DECLASSIFICATION/DOWNGRADING SCHEDULE	3 DISTRIBUTION/AVAILABILITY OF REPORT A Statement
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NWC TP 6827	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Naval Weapons Center 6b. OFFICE SYMBOL (If Applicable)	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code) China Lake, CA 93555-6001	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION Naval Civil Engineering Laboratory 8b OFFICE SYMBOL (If Applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code) Port Hueneme, CA	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO 63724N; PROJECT NO RO829; TASK NO RO829; WORK UNIT NO

11 TITLE (*Include Security Classification*)

GEOTHERMAL POTENTIAL OF MARINE CORPS AIR STATION, YUMA, ARIZONA, AND THE WESTERN PORTION OF LUKE-WILLIAMS GUNNERY RANGE

12 PERSONAL AUTHOR(S)

Bjornstad, Steven C., and Katzenstein, Allan M.

13a TYPE OF REPORT	13b. TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Progress	From 1984 To 1987	1988, January	58

16 SUPPLEMENTARY NOTATION

17 COSATI CODES

FIELD	GROUP	SUB-GROUP
08	07	
08	08	

18 SUBJECT TERMS (*Continue on reverse side if necessary and identify by block number*)

19 ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report details the geothermal resource exploration program at the U.S. Marine Corps Air Station, Yuma, Arizona, and vicinity, as requested by the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California. The purpose of the program was to provide NCEL and the Marine Corps with information on the geothermal potential of the site. The study combines the geothermal information gathered by previous studies with current ideas concerning the tectonic and hydrothermal history of the area and the results of recent field work done by the NWC Geothermal Program Office to develop a broader picture of the factors influencing the occurrence of geothermal resources beneath Department of Navy lands.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL Steven C. Bjornstad	22b TELEPHONE (Include Area Code) 619-939-3411	22c OFFICE SYMBOL NWC Code 2606

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

19 ABSTRACT (Contd.)

The authors conclude, on the basis of the field evidence in hand today, that a potential low-to-moderate-temperature geothermal resource is indicated in the southwest section of the Luke-Williams Gunnery Range. In addition, the authors believe that a slight, but untested, potential exists for a low-to-moderate geothermal resource in the crystalline basement beneath the air station.

CONTENTS

ACKNOWLEDGMENT

We would like to acknowledge the fine base support that we have been given during our field studies in the Yuma area, especially from the Public Works Office, MCAS, Yuma; former PWO Cdr. Len Alfredson; present PWO LCdr. Michael Perry; and their staff. Also, we would like to extend our special thanks to the Transportation Department in Public Works, MCAS, Yuma, for the excellent help they gave our field crews in repairing field vehicles, which helped avert serious problems on the gunnery range. A number of present and former Geothermal Program Office personnel have made contributions to the study of geothermal resource potential at MCAS, Yuma, in the form of literature research, gravity and land magnetic surveys, and data processing and interpretation. Among these are Terri Atienza-Moore, Charlie Rodgers, Dawn Janney, Jack Neffew, BUCS Ted Mort, and Ben Swann.

INTRODUCTION

The Geothermal Program Office (GEOPROFF) at the Naval Weapons Center (NWC), China Lake, California, was tasked by the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California, to perform a geothermal resource exploration program at the U.S. Marine Corps Air Station, Yuma, Arizona, and vicinity. The purpose of the program was to provide NCEL and the Marine Corps with information on the geothermal potential of the site.

Several studies of the geothermal potential of southwestern Arizona, and in particular, south Yuma County, have been conducted in recent years for local and government agencies (References 1 through 5). The most recent study (Reference 5) was completed in 1985 for the Department of Energy by the Arizona Solar Energy Commission.

The present study seeks to combine the geothermal information gathered by these previous studies with current ideas concerning the tectonic and hydrothermal history of the area and the results of recent field work done by GEOPROFF to develop a broader picture of the factors influencing the occurrence of geothermal resources in the Yuma area, and specifically, the potential for geothermal resources beneath Department of Navy lands. In so doing, we will seek to identify/verify the appropriate exploration models and will identify additional work necessary to verify or invalidate these models.

LOCATION AND LAND STATUS

The area of investigation for this report is in two distinct sections: Marine Corps Air Station (MCAS), Yuma, and the western section of Luke-Williams Air Force Bombing and Gunnery Range (R-2301).

MCAS, Yuma, occupies approximately 5 square miles of the Yuma Mesa in southwestern Arizona. The north and northwestern sides of the base are bordered by the City of Yuma, while the remainder is surrounded by agricultural land, primarily citrus crops (Figures 1 and 2). Table 1 is a summary of the land status of MCAS, Yuma.

Luke-Williams Range is controlled by the U.S. Air Force and covers a large section of southwestern Arizona. By a Memorandum of Understanding between the Departments of the Air Force, Navy, and Interior and the U.S. Fish and Wildlife Service, the Range is augmented by the Cabeza Prieta Game Reserve for use in air-to-air gunnery. The game reserve is located

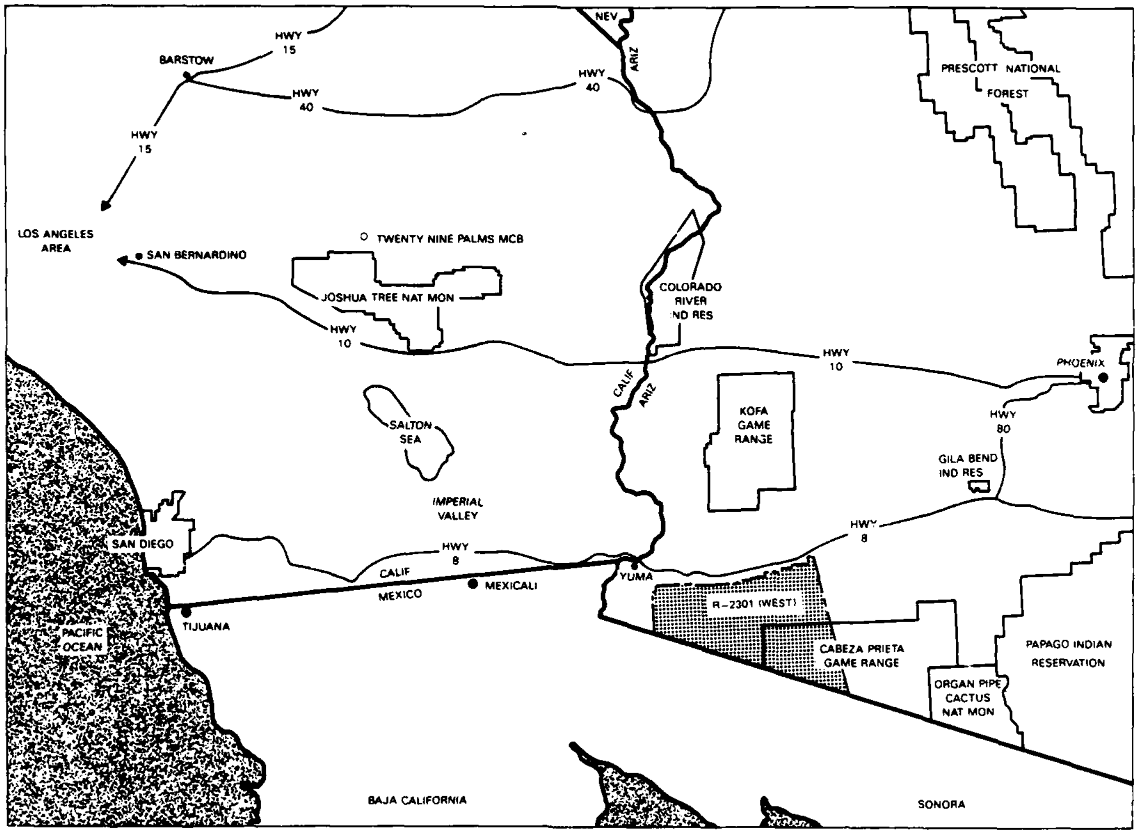


FIGURE 1. Geographic Map of Western Arizona - Southern California.

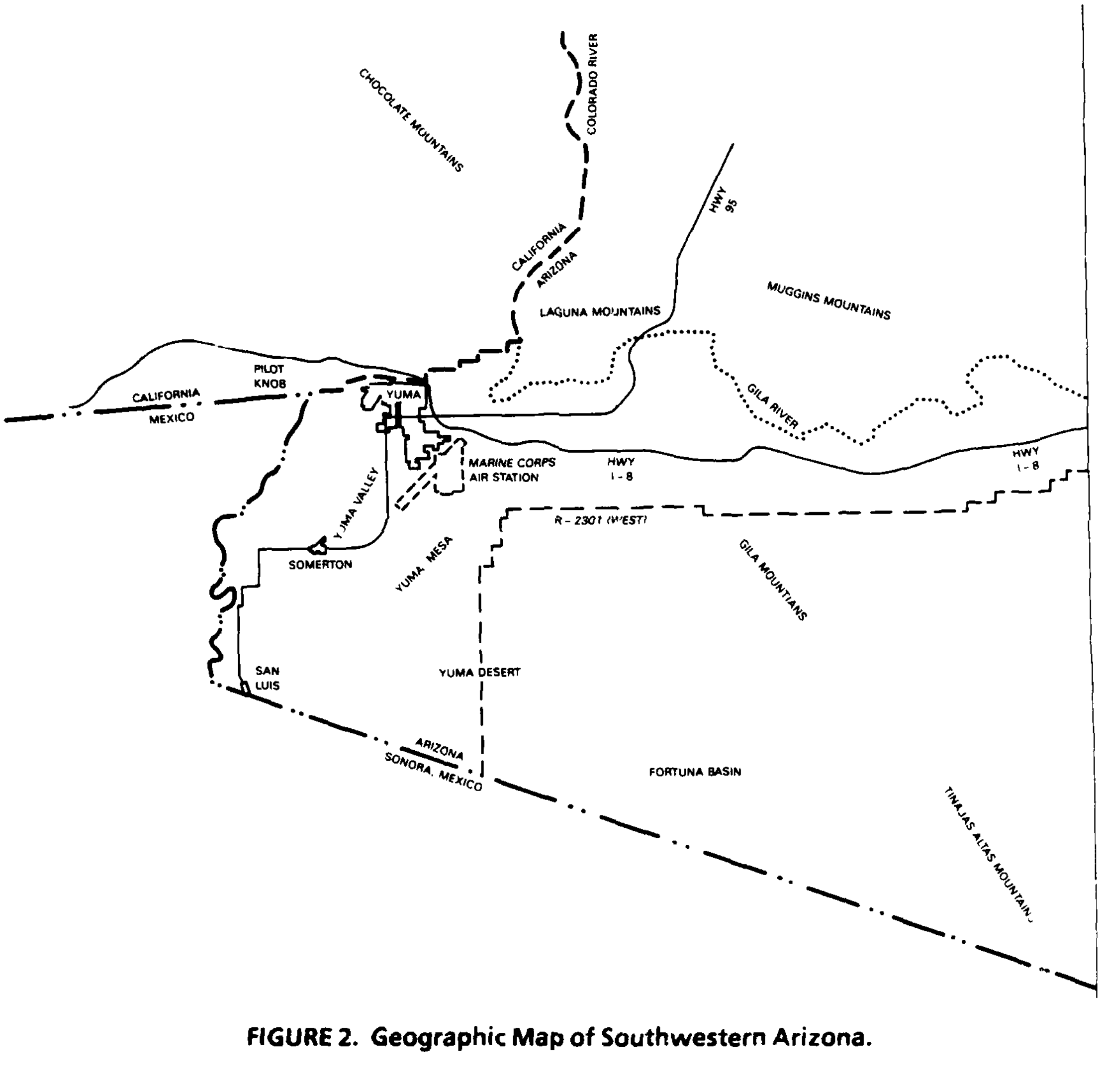


FIGURE 2. Geographic Map of Southwestern Arizona.

TABLE 1. Real Estate Acreage Summary, MCAS, Yuma.
Source: Marine Corps Air Station, Yuma, Arizona,
Real Estate Summary Maps, NAVFACENGCOM, WESTDIV, San Bruno,
California, 1984.

Estate	Acquisitions	Encumbrances and outgrants	
Fee	2457.22	Lease	140.37
Easement	159.59	Easement	34.03
Lease	235.86	Agreement	19.98
Public land order	205.62	Easement patent	175.28
Other	36.07		
Total acres	3094.36	Total acres	369.66

adjacent to the south boundary of the Range. The combined area of the Range covers more than 5200 square miles of the state along the Arizona-Sonora, Mexico, border. Through a Joint Use Agreement between the Commander, Western Sea Frontier, and the Commander, Tactical Air Command, the western half of the Range (R-2301 West), approximately 1500 square miles, is used by the Navy as a gunnery range. The westernmost portion of the Range, approximately 250 square miles, extends into the Yuma Desert adjacent to and southeast of the Yuma Valley, as seen in Figure 2.

The climate in the Yuma Valley is characterized as desert with mild winters and hot summers. For the 29-year period prior to 1977, the mean annual temperature was 73.8°F, with extremes ranging from 24 to 123°F. Annual precipitation for this same period was 2.57 inches (Reference 6).

GEOLOGY

The geologic time scale in Table 2 is included for reference.

TABLE 2. Partial Geologic Time Scale, Millions of Years Before Present (MYBP).
Source: *AGI Data Sheets: for geology in the field, laboratory, and office*, American Geological Institute, 1982.

Era	Period	Epoch	MYBP
Cenozoic	Quaternary	Recent	0.1
"	Tertiary	Pleistocene	2
"	"	Pliocene	5
"	"	Miocene	24
"	"	Oligocene	38
"	"	Eocene	55
"	"	Paleocene	63
Mesozoic	Cretaceous		138
"pre-Cretaceous"		...	...

REGIONAL PHYSIOGRAPHY

The area of this investigation lies along the west side of the Sonoran Desert section and the east side of the Salton Trough section of the Basin and Range physiographic province. MCAS, Yuma, is situated adjacent to the City of Yuma and is located near the junction of the Colorado and Gila Rivers, near the upper end of the Colorado delta. The area is characterized by broad desert plains and river flood plains, above which rise low-lying, rugged mountains.

The Colorado River enters the area from the north, flowing between the Laguna and Chocolate Mountains, while the Gila River enters the area from the east through a similar gap between the Gila and Laguna Mountains. As the rivers leave the mountains they flow across recent flood plains where they join just east of Yuma. The river flood plains are bordered by terraces and piedmont slopes that make up the broad desert plains. These broad, relatively flat areas range in elevation from about 90 feet in the southwest corner of Arizona to about 1000 feet at the base of the Chocolate Mountains. The westernmost section of Luke-Williams Range lies on one of these piedmont slopes. That section stretches westward from the Gila Mountains and includes the Yuma desert and sand dunes.

The southwestern part of the Sonoran Desert is characterized by elongate low mountain ranges trending generally north-northwest (N 20°-40° W). The average structural grain seems to continue farther west, but regional subsidence has occurred in the Salton Trough and bordering area such that only the summits of some of the mountain blocks now extend above the surrounding alluvial fill, while other blocks are completely buried.

The average elevation of the mountains in the area is less than 2000 feet with a maximum of 3150 feet in the southeastern Gila Mountains.

MAJOR ROCK UNITS

For the purpose of our study the rocks and sediments in the Yuma area are grouped into the following major units (from oldest to youngest with some overlap):

1. Basement complex, composed of metamorphic, plutonic, and dike rocks (pre-Tertiary)
2. Nonmarine sedimentary rocks (Tertiary)
3. Volcanic rocks (Tertiary and younger)
4. Older marine sedimentary rocks (Tertiary)
5. Bouse Formation, consisting of younger marine sedimentary rocks (Pliocene)
6. Transition zone (Pliocene)
7. Conglomerate of Chocolate Mountains (Tertiary and Quaternary)
8. Alluvium deposited by the Colorado and Gila Rivers and their tributaries, and minor windblown deposits (Pliocene and Holocene)

The inferred stratigraphic relationships of these units are shown in Figure 3, and their surface exposures are shown in Figure 4.

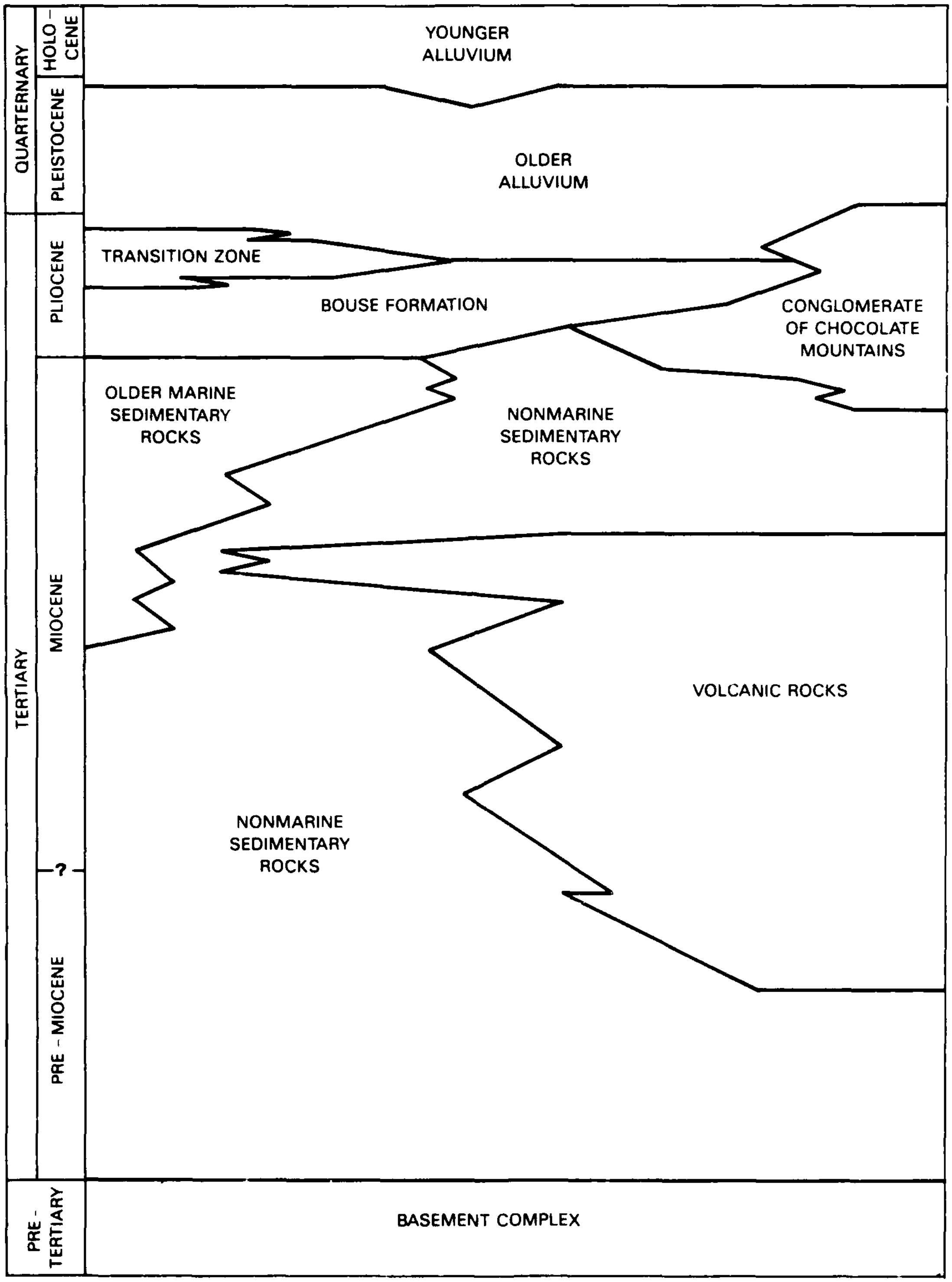


FIGURE 3. Stratigraphic Relations of the Major Rock Units in the Yuma Area.

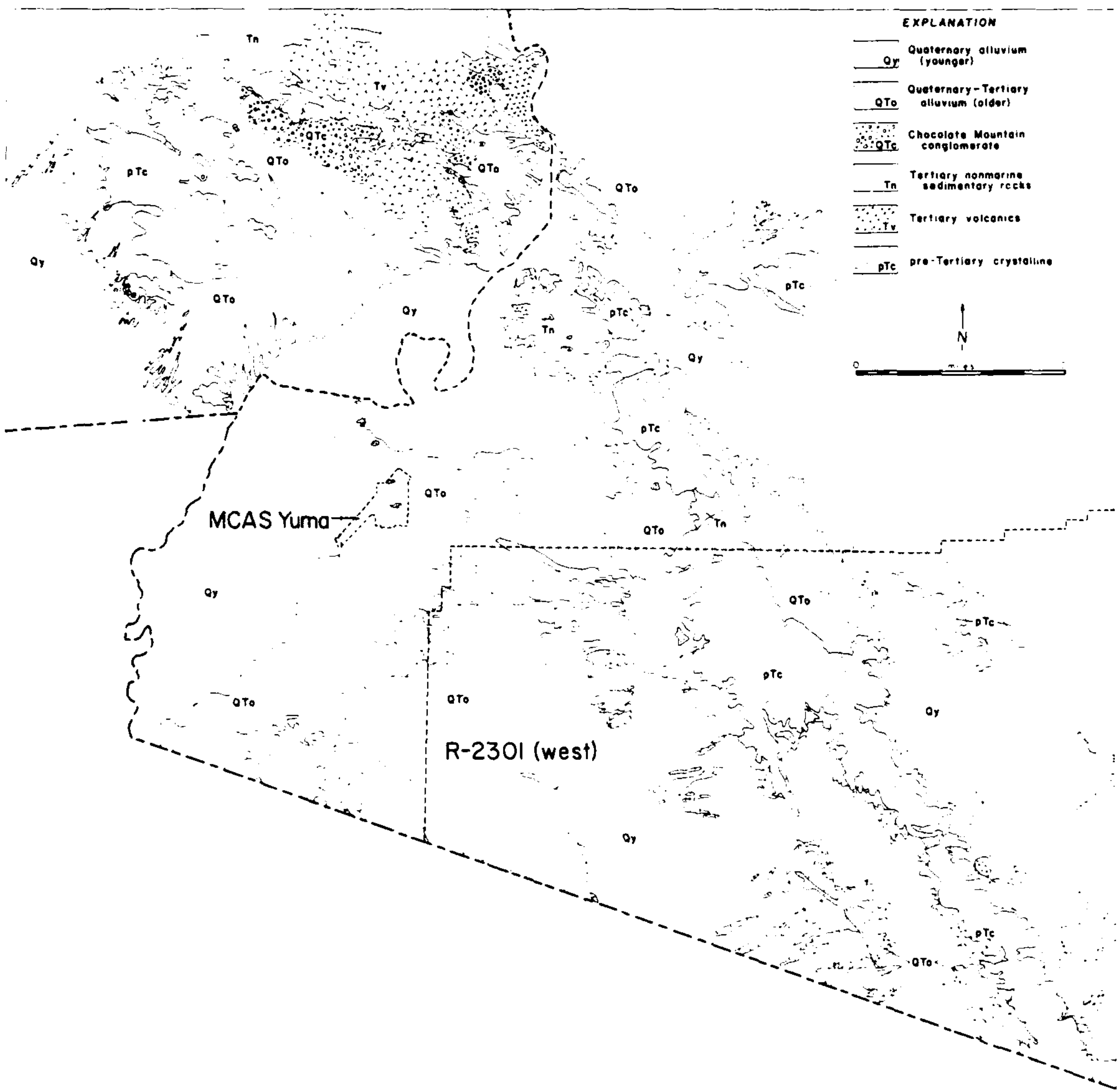


FIGURE 4. Geologic Map of the Yuma, Arizona, Area.

The following general discussion of the stratigraphy of this area has been taken in part from Reference 7.

The pre-Tertiary basement complex consists of a variety of igneous and metamorphic rocks, of which granitic rocks and various kinds of gneiss and schist are most abundant. The entire complex has been invaded by sills and dikes composed chiefly of pegmatite, aplite, and (now-altered) fine-grained mafic rocks. A distinctive porphyritic quartz monzonite, locally gneissic and containing large phenocrysts (or porphyroblasts) of potassium feldspar and irregular patches and streaks of fine-grained biotite, is perhaps the most widespread basement rock type. Stratigraphic relationships and radiometric data indicate that all of the basement rocks predate the late Cretaceous to early Tertiary Laramide orogeny. (A rubidium-strontium age of 73 million years before present (MYBP) from biotite in a granite from a locality at Yuma probably indicates Laramide metamorphism rather than the cooling of the granitic melt.) Some of the dikes and sills may be earliest Tertiary.

The Tertiary nonmarine sediments outcrop on the flanks of some of the mountains and underlie most of the alluvium beneath the plains. Fanglomerate appears to be the most widespread type of unit, although the rocks range from mudstone and shale to megabreccia and boulder conglomerate. The maximum thickness of this unit is unknown, but at least 5000 feet of it is exposed in both the Laguna and Chocolate Mountains, and the combined stratigraphic interval exposed may be more than 10,000 feet.

The Tertiary volcanic rocks found in the subsurface, and exposed extensively in the Chocolate Mountains, are interbedded with the nonmarine sediments. Included in this unit are tuffs and flows ranging in composition from basalt or basaltic andesite to rhyolite. The combined thickness of the unit is more than 2000 feet. Potassium-argon dates from the vast majority of volcanics in both the Chocolate and Laguna Mountains range from 23 to 26 MYBP (middle Tertiary).

Some more recent volcanic activity is scattered throughout the area. A basaltic formation in the Chocolate Mountains of California has been dated at 13.1 ± 2.5 MYBP (Reference 8). The Cerro Pinacate volcanic field in northern Sonora, Mexico, is thought to be Quaternary in age (Reference 9). The Sierra Pinacate basaltic field in southeastern Yuma County has yielded potassium-argon ages of 0.465 ± 0.065 and 0.461 ± 0.036 MYBP (Reference 10).

The older marine sedimentary rocks are composed of somewhat indurated fine-grained sandstone and interbedded siltstone and claystone. Their age is uncertain, but they appear to intertongue with the upper part of the Tertiary nonmarine sediments. These older marine sedimentary rocks occur entirely in the subsurface and have a maximum known thickness of about 1000 feet.

These sediments are the target of sporadic petroleum wildcatting in the Colorado delta. This wildcatting has met with marginal to moderate success to date, primarily in the lower delta region in Mexico. The potential for the occurrence of economic quantities of petroleum beneath the Navy land near Yuma is generally thought to be slight; however, there are petroleum explorationists working in the area, and at least one independent

believes there may be some potential beneath the Fortuna Basin (the southwestern part of the Luke-Williams Gunnery Range.)*

The Bouse Formation is a younger marine unit (Pliocene) which, except for one small exposure near the Imperial Dam, occurs only in the subsurface within the Yuma area. This formation is more extensive than are the underlying older marine sediments and represents the deposits of a marine embayment that existed after the mountains and basins had assumed approximately their present outlines. The unit consists of silt and clay with thin interbeds of fine sand, hard calcareous claystone, and some local limy sandstone, tuff, and conglomerate. This unit marks the floor of the main part of the ground-water reservoir and ranges up to 1000 feet thick in the southwestern part of the area.

Throughout the central and southern parts of the study area, primarily south of the Colorado River, the Bouse Formation is overlain by a transition zone of intertonguing marine and nonmarine (fluvial) strata. The base of this unit is marked by the lowest identifiable alluvium from the Colorado River; the top, by the uppermost bed of fossiliferous marine clay or silt. The transition zone has a maximum thickness exceeding 850 feet.

The conglomerate of the Chocolate Mountains has been identified only along the flanks of these mountains. It is made up primarily of volcanic detritus that is stratigraphically equivalent to both the upper part of the Tertiary nonmarine sediments and the lower part of the alluvium.

The alluvial deposits of Pliocene to Holocene age range from clay to cobble and boulder gravel. This gravel is the predominant fraction at most places, silt and clay constituting less than 20% of the total thickness. Cementation is uncommon, and the alluvium contains most of the usable ground water of the Yuma area.

REGIONAL STRUCTURE AND TECTONIC HISTORY

The southwestern part of the Sonoran Desert east of Yuma is characterized generally by long, narrow mountain ranges separated by more extensive desert plains. The mountains are composed chiefly of pre-Tertiary plutonic and metamorphic rocks, although Cenozoic volcanic and minor sedimentary rocks are locally extensive. The intervening desert plains are basins containing thick Cenozoic to Recent fill.

The mountain ranges, most of which are oriented north-northwest, are elevated or tilted fault blocks bounded at the surface and near-surface by steep faults and are classically thought to have been formed by structural activity consisting chiefly of extensive faulting and tilting in middle Tertiary and pre-Tertiary time (Basin and Range structure). Recent rethinking of the Basin and Range structural problem has resurrected other interpretations that place more emphasis on the overall compressional nature of the tectonic forces that have been at work in these areas (References 11 through 13). Later movements have consisted

* Personal communication with Mike Bradshaw, President, Contender Oil Co., Yuma, Arizona, January 1987.

chiefly of minor warping and normal faulting and of regional subsidence near the west margin of the area, adjacent to the Salton Trough.

The Salton Trough is a deep basin that subsided rapidly during the Cenozoic time and accumulated as much as 20,000 feet of fill. Most of this fill is nonmarine, much of it coming from the Colorado River. In contrast to the Sonoran Desert, the Salton Trough has been tectonically active to the present. The trough is formed on northwest-trending high-angle faults of the transform San Andreas system, on which the major component of movement has been right-lateral. The Gulf of California--the southern extension of the Salton Trough--has been interpreted as having been formed by oblique rifting across the fault system and probably also by ocean-floor spreading (Reference 14).

The northeasternmost major fault in the San Andreas system in the Yuma area is the Algodones fault (Figure 5). The Algodones may be a continuation of the San Andreas fault to the northwest and is a feature of major hydrologic significance in the Yuma area (Reference 15).

Shafiqullah and others and Aldrich and Laughlin (References 16 and 17) reviewed the chronology of rocks in southwestern Arizona and vicinity using potassium-argon (K-Ar) age data gathered over the previous 20 years. (K-Ar dating measures the timing of the magmatic and tectonic events that create and/or deform rocks.) Figure 6 is a map of the Yuma County area with sample locations and radiometric data ranges. The actual rock type and age determination of each sample location is given in Appendix Table A-1, which was compiled from References *10, 16, and 17*.

According to Morrison and Menges (Reference 18), the high-angle faulting attributed to Basin and Range deformation ceased in the Sonora Desert region in the middle Pleistocene, and thus this area has been historically aseismic; however, in the Yuma basin approximatey 50 faults of early to late Pleistocene (possibly Holocene) age have been identified. All of the faults are oriented generally northwest and have lengths of 2 to 13 kilometers and scarp heights (vertical discontinuity) of 3 to 60 meters. Although a number of the faults mapped in the basin show significant strike-slip movement (San Andreas-type motion), the abundant evidence of dip-slip motion indicates continued subsidence of this section of the Salton Trough.

GEOPHYSICAL STRUCTURAL FEATURES

The major structural features of the Yuma area are delineated by gravity and aeromagnetic data. A Bouguer gravity map of the area is shown as Figure 7. Gravity highs are associated with all known exposures of the pre-Tertiary basement complex, and gravity lows with all areas known to be underlain by thick Cenozoic sedimentary fill. Large variations in Bouguer anomaly values not related to the valley fill have been attributed both to variations in the density of the basement and to a regional anomaly associated with the Salton Trough. For example, on the west side of the Gila Mountains, near the Fortuna mine, the gravity values are about −10 milligals (mgal). This is due, presumably, to the abundance of dense hornblende schist and gneiss; whereas farther south, less dense leucocratic granite is exposed, and the gravity values near basement outcrops decrease to about −30 mgal (Reference 7).

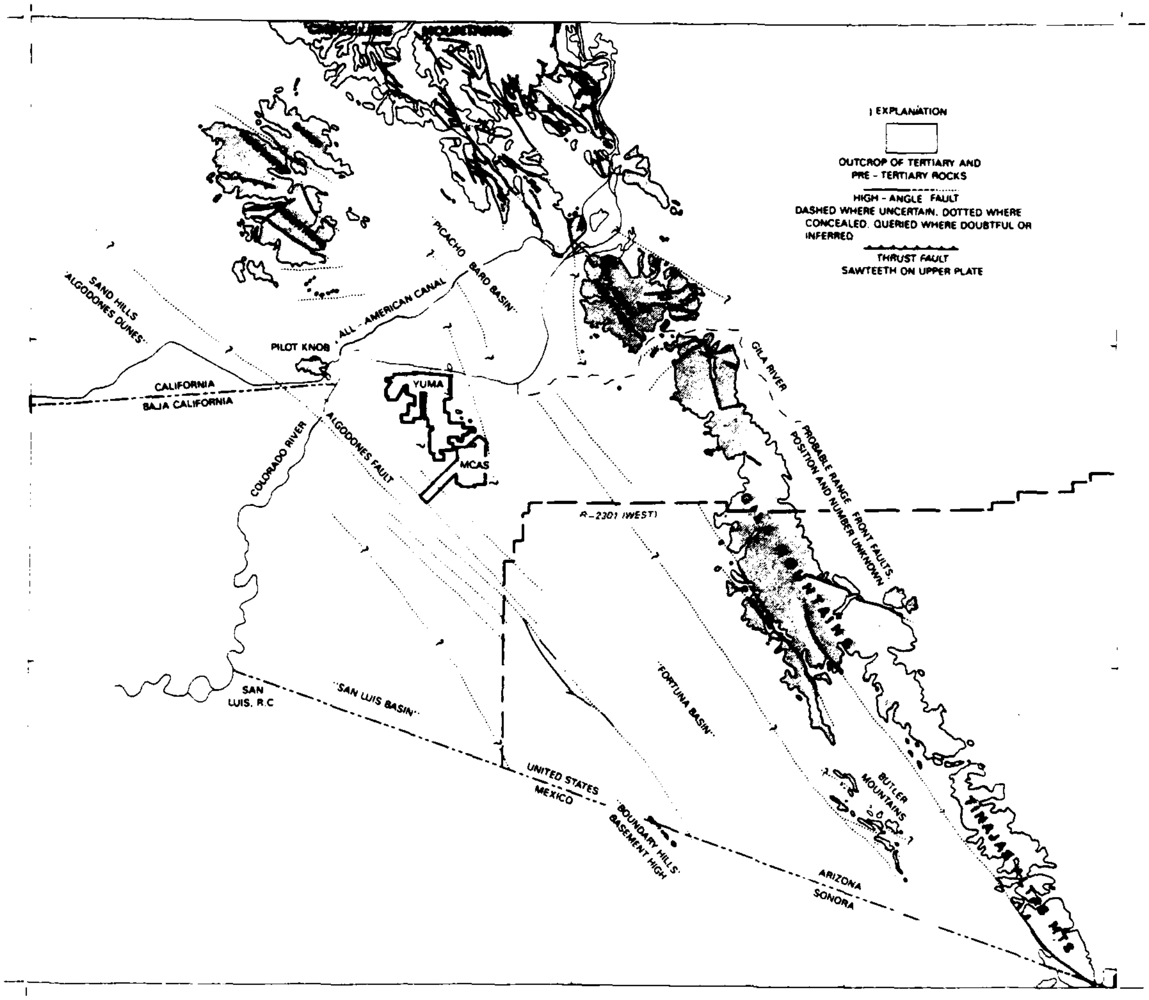
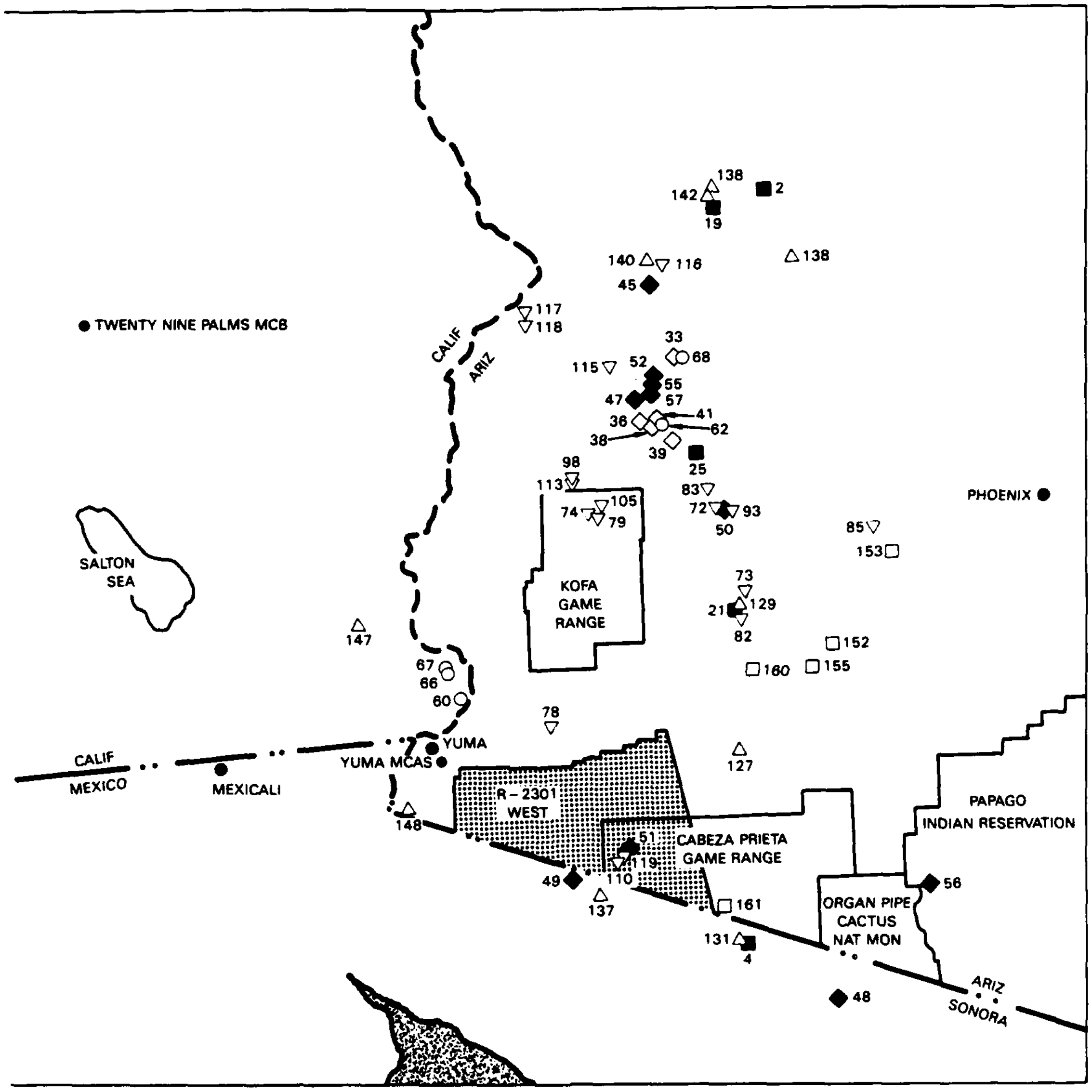


FIGURE 5. Principal Geologic Structural Features.



LEGEND	MYBP
□ QUATERNARY	2 – 0
PLIOCENE	5 – 2
△ MID - TO LATE MIOCENE	14 – 5
▽ EARLY TO MID - MIOCENE	24 – 14
○ OLIGOCENE	38 – 24
◆ EOCENE	55 - 38
PALEOCENE	63 - 55
◇ CRETACEOUS	138 - 63
■ PRE - CRETACEOUS	- 138

FIGURE 6. Location of Cretaceous to Quaternary Rock, Yuma County, Arizona, and Vicinity.

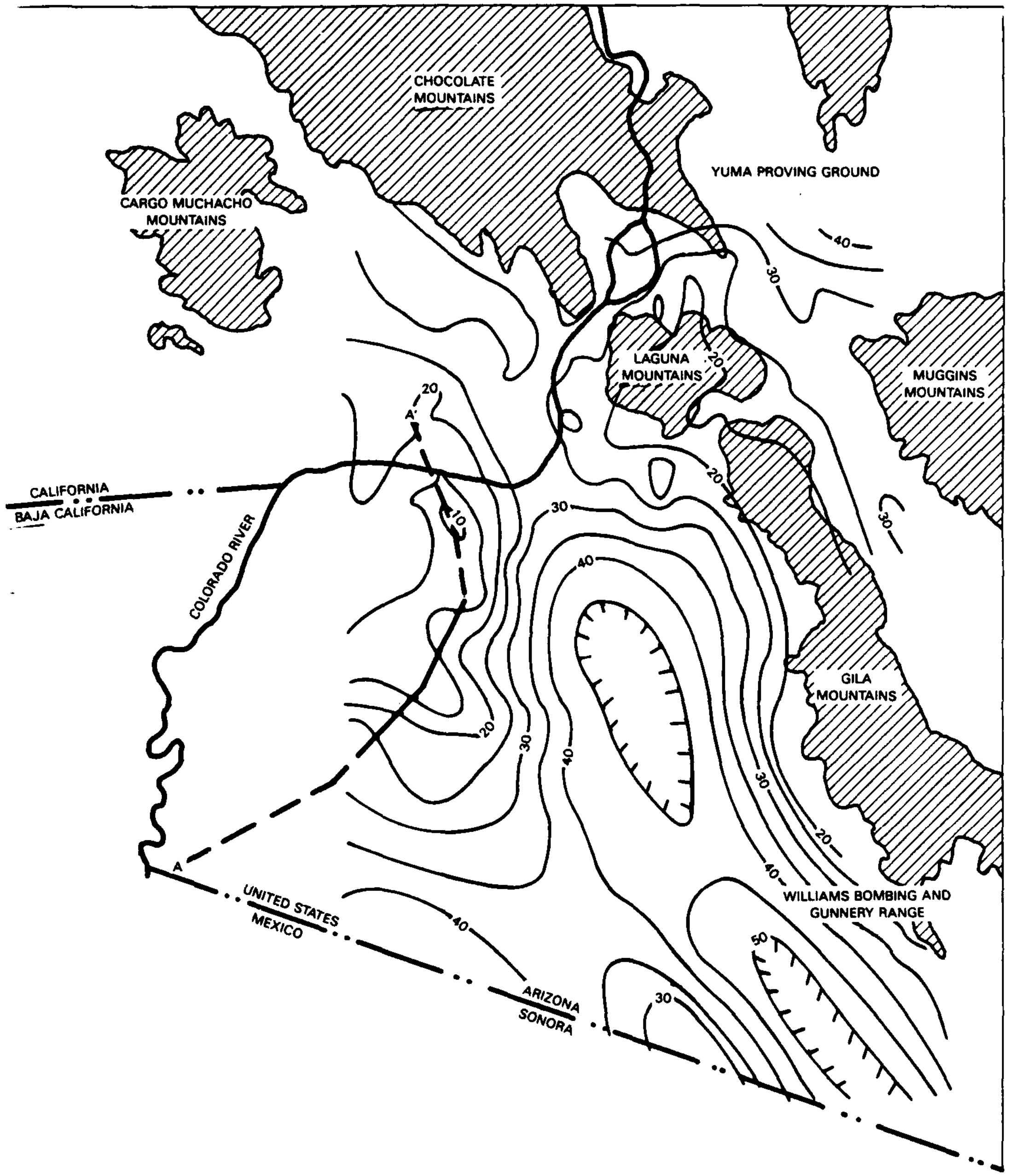


FIGURE 7. Regional Gravity Map.

Gravity surveys in the Colorado River delta region have revealed a major gravity high presumably associated with a thinning of the crust under the Salton Trough. This regional gravity anomaly probably extends into the Yuma area and gives rise to an east-northeastward decrease in anomaly values across the area. The regional gradient, however, does not appear to be significant, at least in comparison with the amplitudes of local anomalies in the Yuma area (Reference 7).

The following are some of the significant gravity anomalies in the Yuma area:

- A gravity saddle between the Cargo Muchacho Mountains and Pilot Knob reflects a significant alluvial gap through which ground water now moves westward from the Yuma area toward Imperial Valley.

- A multiple-crested gravity high (the Yuma basement high) extends roughly southward from Yuma and comprises two main parts: the northern part, called the Yuma anomaly; and the southern part, called the Mesa anomaly. MCAS, Yuma, is situated on the saddle between these two anomalies and on a south limb of the Yuma anomaly.

- A gravity high is centered on basement outcrops on the border with Sonora, Mexico, and separated from the Yuma basement high by a deep, broad gravity saddle; the associated structural feature is designated the Boundary basement high.

- A gravity trough is located between Yuma and Pilot Knob; its associated structural feature is designated the Yuma trough.

These anomalies may also be seen in the cross section in Figure 8.

Aeromagnetic, seismic-refraction, seismic-reflection, and resistivity surveys have also been done over this area. The aeromagnetic map (Figure 9) shows the same major structural features as does the gravity map. The Yuma basement high, the Yuma trough, and the Fortuna Basin are all shown by the magnetic data. Resistivity and the seismic surveys have been done by the U.S. Geological Survey for comparison with the other surveys and to better delineate certain features, such as the basement highs and the Algodones fault (Reference 7). Seismic-reflection surveys have recently been done in several areas in the greater Yuma Valley. These surveys gathered proprietary data on the configuration of deep basin sediments and are being used for petroleum exploration. Both the Algodones fault system and a section of rapidly thickening deltaic/valley-fill sediments are apparent in cross sections from these surveys.

Efforts to produce a single geophysical lineament map of Arizona using gravity, magnetic, and satellite photos (Figure 10) have resulted in the identification of several trends that may impact geothermal potential in the Yuma area (Reference 9). A large group of west-northwest trending lineaments, the Texas Strand, is a very prominent feature trending through the central to southcentral part of Arizona. It is not only an alignment of Bouguer and aeromagnetic gradients, it is also a boundary between basement textural provinces. The Texas Strand is thought to be the southern "geophysical" border of the Colorado Plateau because it marks a contrast in magnetic texture signifying a difference in the deeper crust (curie depth is probably shallower south of the strand).

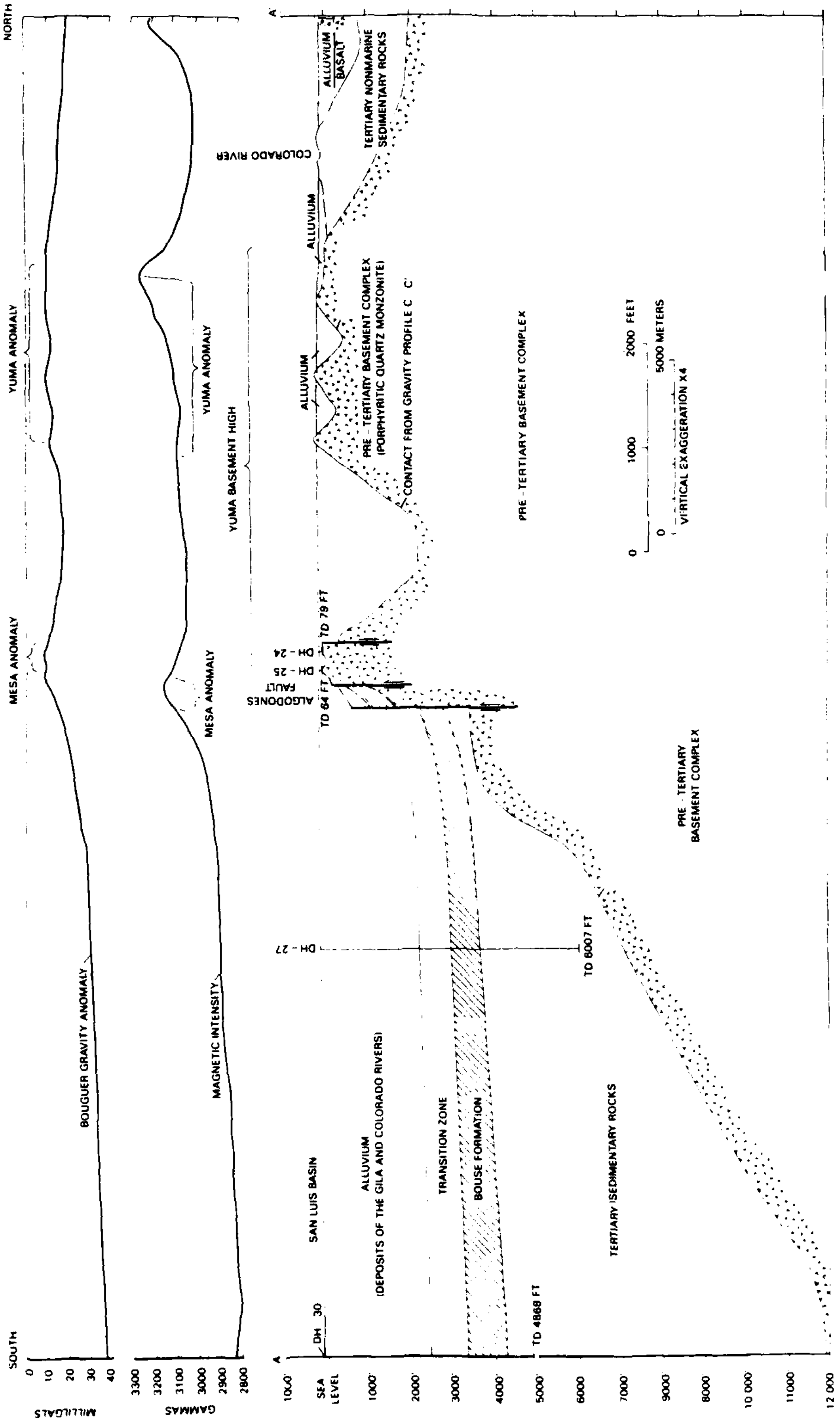


FIGURE 8. Gravity and Magnetic Profile, Yuma Basin.

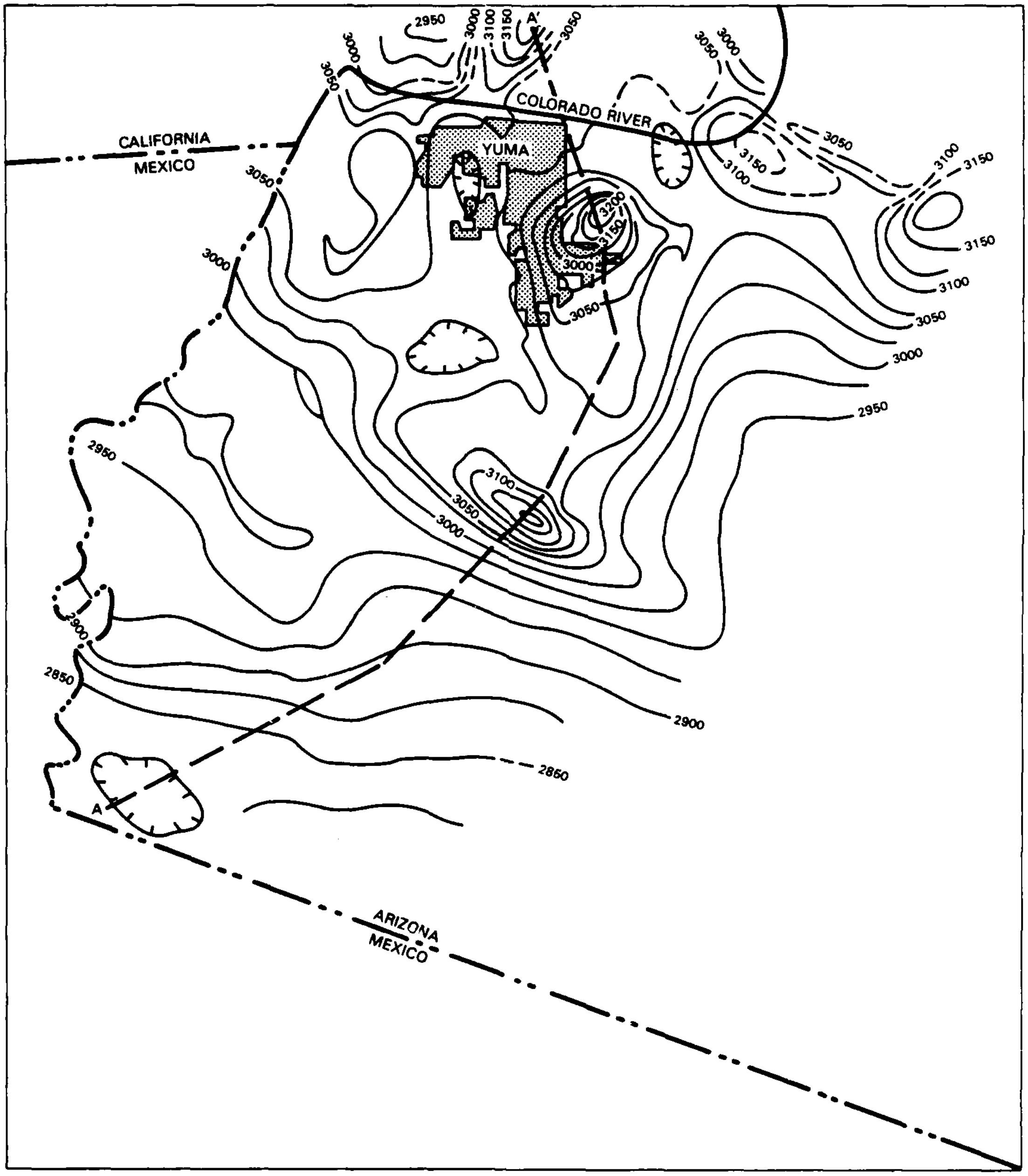


FIGURE 9. Regional Magnetics Map.

Several studies have been made on the Texas trend. This trend and several others in the western U.S. are oriented transverse to the North American plate boundary and it has been argued that these lineaments may play a role in the localization of mineral belts and hydrothermal activity (References 19 and 20). Others have argued that while there may be some relation between mineralization and lineaments or trends, the lineaments are much too irregular to be used as exploration guides (Reference 21). Given the intimate relationship between hydrothermal mineralization and geothermal activity, these arguments are also applicable to geothermal exploration. Figure 10 also shows several geothermal areas in southwestern Arizona that appear to be associated with these geophysical lineaments.

The Gila Trough, generally trending northeast from Yuma through Phoenix, is thought to predate late Miocene (13-12 m.y.) block faulting and was probably associated with the mid-Tertiary (28-17 m.y.) tectonism. Toward Yuma the Gila Trough is offset (right-lateral?) by the San Andreas trends (five of them) and is not obviously present west of these lineaments, at least not in Arizona.

Because Arizona is transected by the Texas Strand lineament, Yuma appears to be beyond its direct influence. There are, however, other systems trending in the "Texas" direction in the south part of the state, including the Yuma area. The Crater Mountain and Cowlick lineaments may be the result of similar events that caused the Texas Strand. It is interesting to note that the Quaternary Cerro Pinacate lava field lies at the three-way intersection of an unnamed west-northwest system lying just south of the Arizona-Sonora border, a San Andreas lineament, and the Pinacate system.

Lepley (Reference 9) indicates that the major lineament systems in Arizona correlate reasonably well with known geothermal areas and occurrences. Many of the major systems are old--Precambrian, Paleozoic, and Mesozoic--but they appear to control the location of Quaternary volcanic systems, according to Lepley. Radium and Agua Caliente Hot Springs (and the area of above-normal temperature gradient associated with them) are, generally, in the Gila Trough trend as are the most recent volcanics in Yuma County (Figure 6). If the Gila Trough is projected through the San Andreas trends (with appropriate offsets), oil exploration well Exxon Federal #1, near the Mexican border, is also in the trend (see section on Geothermometry). The offsets and other irregularities in the Yuma basement high anomaly may be the result of the intersection of the Gila trend and the major San Andreas trend (the Algodones fault).

HYDROLOGY

The ground-water reservoir in the Yuma area is composed of Cenozoic basin-fill deposits overlying the pre-Tertiary crystalline basement. The thickness of fill in the deepest parts of the basin probably exceeds 16,000 feet, but only the upper section (2000 to 2500 feet, maximum) is composed of fresh-water-bearing alluvial deposits.

The two major subdivisions within the reservoir are (1) the lower section consisting of sedimentary and related rocks of Tertiary age, and (2) the upper alluvial deposits of Pliocene to Holocene (or Recent) age. The lower section includes all the stratigraphic units below and including the Bouse Formation and transition zone. Based primarily on electric logs of oil exploration wells, it appears that this lower section contains saline to very brackish water.

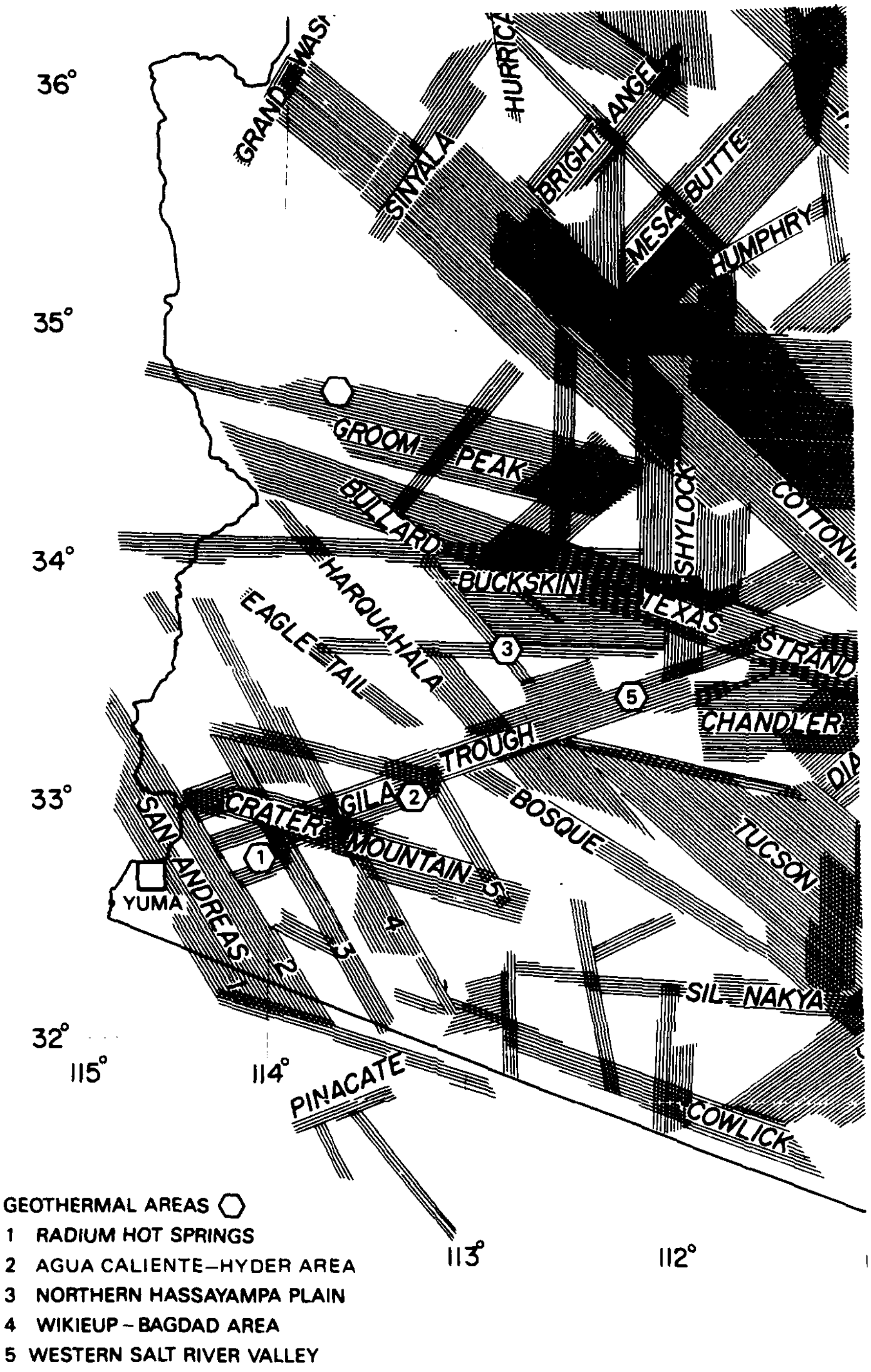


FIGURE 10. Lineament Map.

The upper section of the reservoir includes the older alluvium, younger alluvium, and windblown sand units. These upper units contain most of the fresh ground water and, as such, are the most accessible today. Through the monitoring efforts of the Bureau of Reclamation, nearly all the recent information on the hydrology of the area comes from this upper section.

The climate in the Yuma area is typical of southwestern deserts, and as rainfall averages about 3 inches per year, agriculture is possible only with irrigation. Before settlements were established in Yuma Valley, almost all the water in the upper part of the ground-water reservoir in the Yuma area consisted of natural recharge of river water from the Colorado and Gila Rivers infiltrated by natural recharge along the river channels and floodplains. Today, however, nearly all shallow ground-water recharge occurs in conjunction with irrigation practices.

Irrigation of the land for agricultural purposes has been ongoing in the Yuma area since the 16th century when the Pima Indians used Gila River water to irrigate crops. Modern irrigation efforts began in 1857 in Yuma Valley, and major reclamation began with the authorization of the Yuma Project in 1904. Agricultural efforts have continued to evolve. In 1982 about 107,000 acres were irrigated in the Yuma area (Reference 15). Within the main area of interest of this report (Yuma Valley and Yuma Mesa), approximately 67,000 acres were irrigated with about 506,000 acre-feet, or the equivalent of over 7.5 feet of water in 1982. This amount of water movement, and accompanying changes to the chemical constituents of the ground water, will tend to mask any geothermal components that may be leaking into the upper ground-water system.

Olmsted and others (Reference 22) made an extensive study of the geohydrology of the Yuma area with emphasis on the upper few hundred feet of the aquifer (where the vast majority of the data is derived). In it they noted several chemical-change processes that are at work in the ground water including (1) concentration by evapo-transpiration, (2) softening, (3) carbonate precipitation, (4) sulfate reduction, and (5) hardening. These changes effect primarily the salts, chlorides, and sulfates and include most of the major elements that are used as geothermal indicators.

Irrigation also appears to have a pronounced effect on the geothermal gradient in the valley, particularly in the near-surface. Heavy irrigation and large-scale pumping from wells has resulted in enhanced vertical ground-water movement, as well as in erratic horizontal mixing. Figure 11 shows the temperature of ground water in the 100- to 150-foot level. Several warm anomalies are delineated. Most of these anomalies appear to be related to faults or fault zones, although Olmstead and others state that some may reflect hot zones in the pre-Tertiary basement and that others simply reflect areas of reduced transmissivity in the aquifer. A major anomaly along the west margin of northern Yuma Mesa is believed to be directly attributable to the upward movement of ground water that has taken place since irrigation began on the Yuma Mesa.

Except for the westward flow of water between the Cargo Muchacho Mountains and Pilot Knob, the regional direction of ground-water flow is parallel to the Colorado River, south-southwest. As noted earlier, and as shown in Figure 12, the Algodones fault has a major influence on the ground-water reservoir in the Yuma area. On the Upper Mesa, water levels in test wells northeast of the inferred fault trace are more than 30 feet higher than

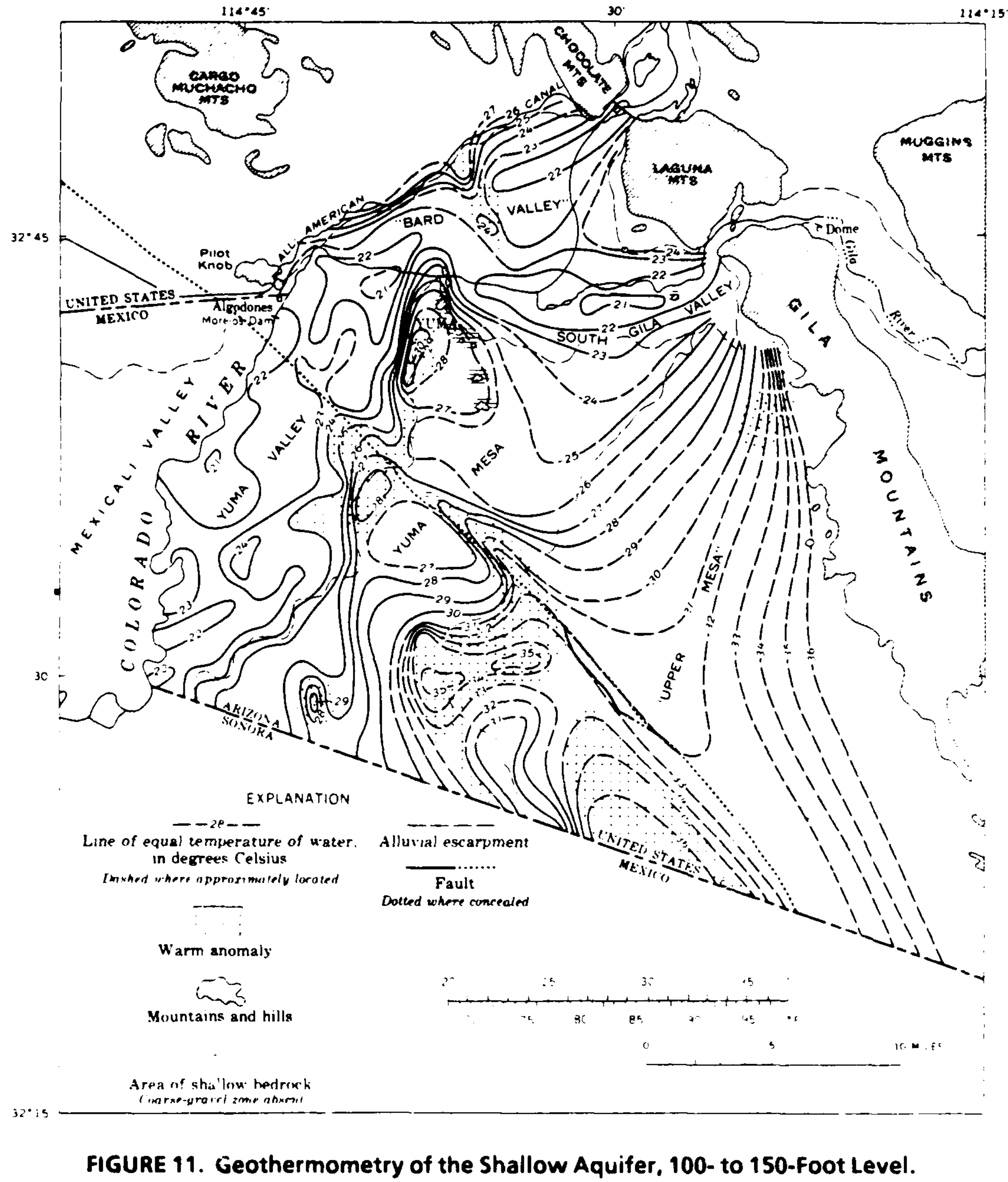


FIGURE 11. Geothermometry of the Shallow Aquifer, 100- to 150-Foot Level.

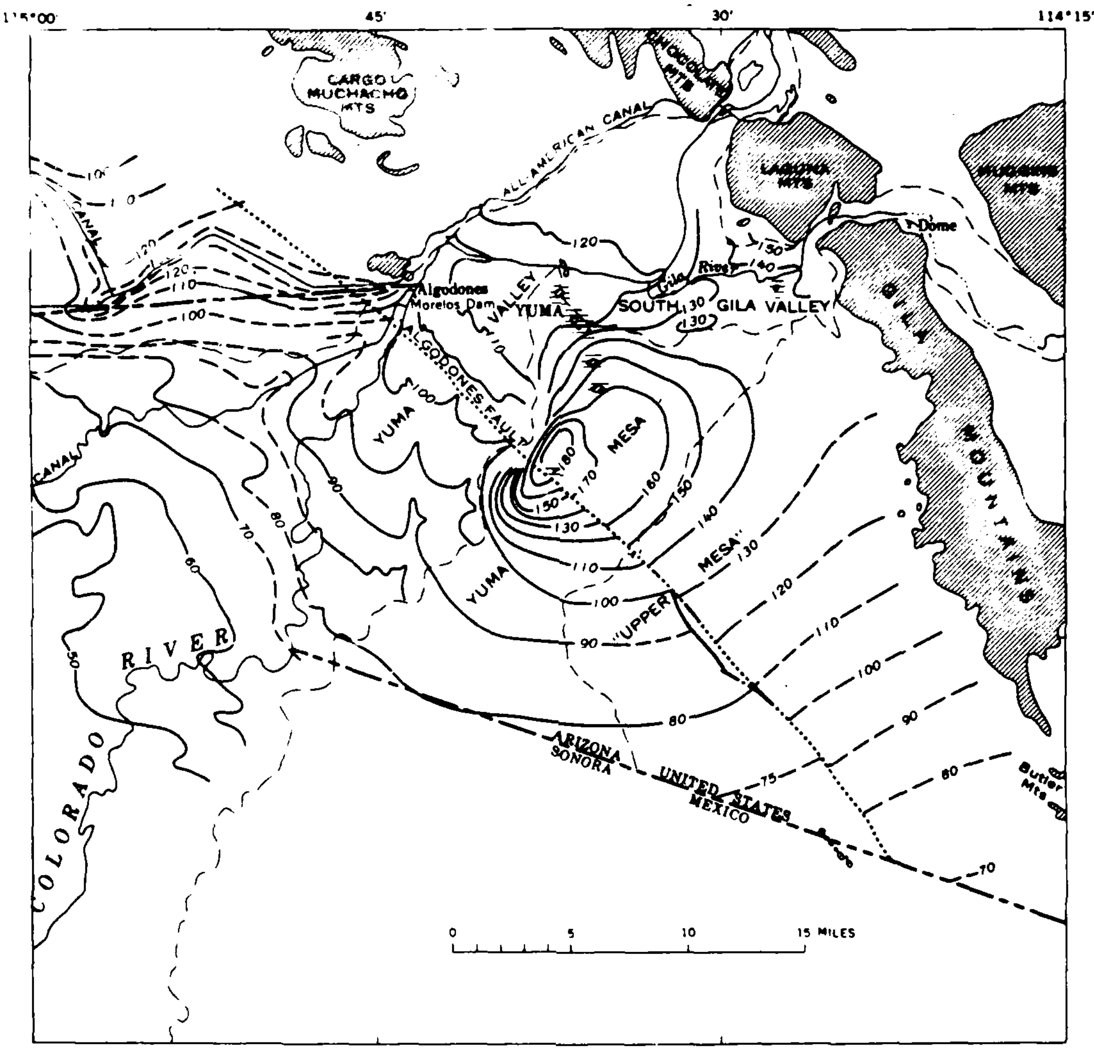


FIGURE 12. Water Level Contours, Yuma Basin, 1965.

those southwest of it. This trend in offset values continues (with smaller differences) southeastward into Mexico and northwestward beneath the Yuma Mesa. This barrier effect is probably caused by a combination of pulverization of materials along the fault, deposition of minerals along the fault surface, and offset of bedding. It is uncertain if this barrier effect continues down into the lower aquifer, but some of the ground-water temperature anomalies that appear to be associated with the Algodones fault may be the result of an upwelling of deeper warm water along the fault surface.

The primary purpose of this discussion of the hydrology of the Yuma area is twofold. First, it points out that the area is underlain by a hydrologic regime that would readily support a sedimentary-type, water-dominated geothermal system. It also shows, however, that one of the best standard tools of geothermal exploration--chemical geothermometry--is of limited use here because of the extensive mixing, contamination, and alteration of the upper aquifer and the very limited access to the underlying, less disturbed waters.

Much of the westernmost portion of R-2301 West is essentially outside the area affected by artificial ground-water movements, but ground-water data points are also very limited. Because of this fact, chemical geothermometry is of limited use in this area as well.

HYDROTHERMAL HISTORY

The most readily available data on the hydrothermal history ("fossil geothermal") of an area are the mining records and geologic studies related to minerals exploration. This is an area that is sometimes ignored in geothermal exploration but can be an additional exploration tool in that it may indicate trends in such things as tectonic influences, fluid movement, and geochemical activity. The latter can offer further clues to present geothermal occurrences, particularly those with subtle or no surface manifestations.

The southwestern Arizona/southeastern California area has been tectonically active since the mid-Mesozoic period and extending to the present. Pulses of major hydrothermal activity in the area appear to have occurred throughout this period as well.

Mineral deposits occur in a large portion of the mountain ranges in and around south Yuma County and have been of economic importance in several districts (Figure 13). These deposits normally occur as veins deposited in fault or fracture zones primarily by ascending hydrothermal solutions and include both mesothermal and epithermal types.

Representative of the mesothermal type are the gold-bearing quartz veins of the Gila, Laguna, Wellton, Copper, Tank, Chocolate, Cargo Muchacho, and Gila Bend ranges, and the argentiferous galena veins of the Castle Dome Mountains and the Middle and Eureka districts of the Arizona Chocolate Mountains. Veins of this type were deposited at depths of more than 3000 feet and at moderately high temperatures and are characterized as localization by fractures with even-to-smooth walls, coarse-grained textures, and wall-rock alteration of carbonate, quartz, and coarse-grained sericite. (The Fortuna mine, located on the west side of the Gila Mountains in R-2301 West, is of this type. It has a lenticular, chimney-like form with smooth fracture surfaces, but shows little notable sericitization of the wall rock.) Although Wilson and Morton believed that the mesothermal deposits were late Mesozoic in age, recent workers in the area have demonstrated that the deposits are

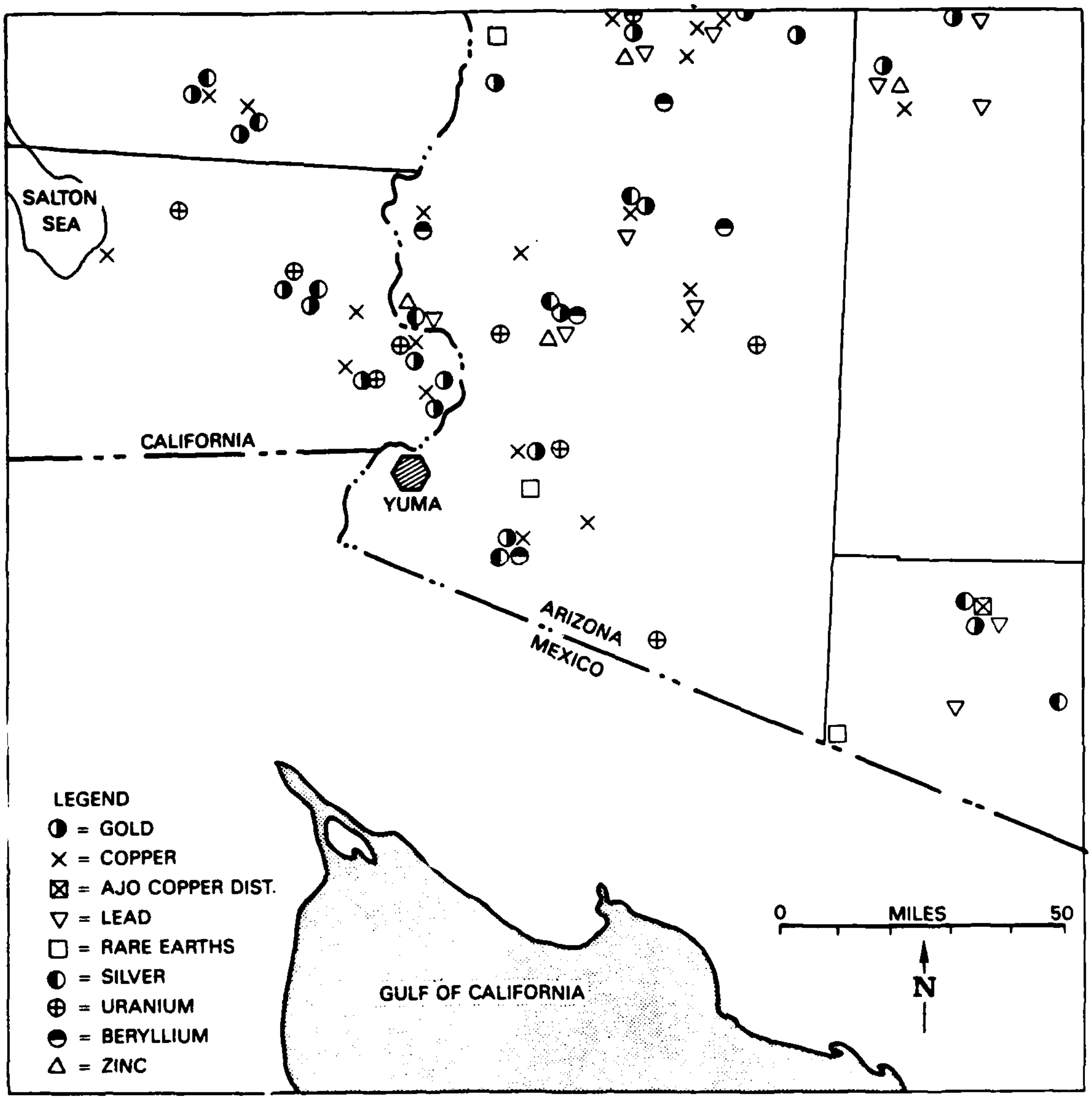


FIGURE 13. Map of Major Mineral Occurrences, Yuma Area.

somewhat younger (References 23 and 24). A reset K-Ar date of 32 to 39 MYBP was determined for the mineralization episode of the Mesquite gold deposit in the Chocolate Mountains in Imperial County, California (Reference 25); the mineralizing system of the American Girl-Padre y Madre gold deposists in the Cargo Muchacho Mountains, also in Imperial County, California, was active during the Eocene (Reference 26); Smith and Graubard (Reference 27) described the Fortuna mine as being "in the mineral belt containing the Mesquite and Picacho mines and the Cargo Muchacho district and is nearly identical to the Tumco mines in this belt."

A single occurrence of ore-grade mineralization appears to have been worked in the immediate Yuma area in the early days of this century. Reference 23 described a small mine that was located in the hill about 2 miles south of the Colorado River, where Highway 95 intersects the Southern Pacific railway from the east. The hill is an outcrop of coarse-grained biotite gneiss, and the mine was developed on fractures filled with veins of coarse-grained quartz, pyrite, limonite, and gold. This mineralization was probably also mid-Tertiary.

Representatives of the epithermal type are the gold-bearing quartz veins of the Kofa and Sheep Tank districts and the lead-silver and barite veins of the silver Mohawk and Neversweat districts. Veins of this type are deposited under conditions of moderately low temperatures, at depths generally less than 3000 feet, and are best developed in the Tertiary volcanic rocks. These veins are characterized by rather irregular form, rich near-surface bodies, fine-grained texture, breccia inclusions, wall-rock alteration to chlorite, carbonate, quartz, and fine-grained sericite. Reference 23 suggests that the epithermal veins were deposited at the close of the Tertiary volcanic activity and that the mesothermal lead-silver veins may also belong to this period.

Except for pegmatite veins and similar mineralization in the older metamorphic and granitic rocks, most of the mineralization appears to be post-Laramide and more recent in age. The mineralization in the far southern mountains of the area--the Gila, Laguna, and Tinajas Altas Mountains--tends to follow the regional, north-northwest "Basin and Range" fracture trends (Reference 28). This activity would have been during the early to mid-Tertiary period.

While several gold placers of economic importance have been found in southern Yuma County, no epithermal gold deposits in gravels of any age have been reported.

The mineral deposits associated (?) with the Tertiary volcanic activity in the Trigo, Castle Dome, Chocolate, Kofa, and other mountains north and northeast are examples of later Tertiary geothermal activity. An example of this is in the Castle Dome Mountains where extensive deposits of Tertiary volcanics (rhyolites, andesites, and tuffs) are locally covered by Quaternary basalts. Dikes of quartz porphyry intruded along fractures within Tertiary volcanics and hydrothermal fluids followed these same fractures and deposited lead-silver and fluorite veins. The Quaternary basalts, however, are barren of mineral deposits.

In general, evidence of "fossil" hydrothermal/geothermal activity in the Yuma area more recent than Tertiary has been difficult to find. Radium Hot Springs, which is now essentially dry, was still active in the 1930s. The site is located on the north bank of the Gila River (Figures 1 and 10) and, according to Reference 23, the thermal waters bubbled up from the mud flat of the river adjacent to a small hill of sericitized andesite. An analysis of the

waters, taken in 1924, is given in Table 3. The radium content was approximately 1.2×10^{-9} grams per liter.

With regard to hydrothermal activity, the Yuma region appears to be a temporal as well as a spatial transition zone between the emplacement of the majority of the Arizona porphyry coppers during the Laramide orogeny in the late Cretaceous to early Tertiary (References 28 and 29) through to the deposition of massive sulfides that is occurring in the Salton Trough today (Reference 30). This spatial and temporal transition is shown graphically in Figure 14.

As noted earlier, there has been active discussion concerning the role of lineations in the localization of mineral belts and hydrothermal activity. If the Texas trend has had an effect on the localization of mineralization (hydrothermal activity) in southwestern Arizona and southeastern California (especially the Yuma area), it is difficult to establish.

LOCAL GRAVITY AND GROUND MAGNETICS SURVEYS

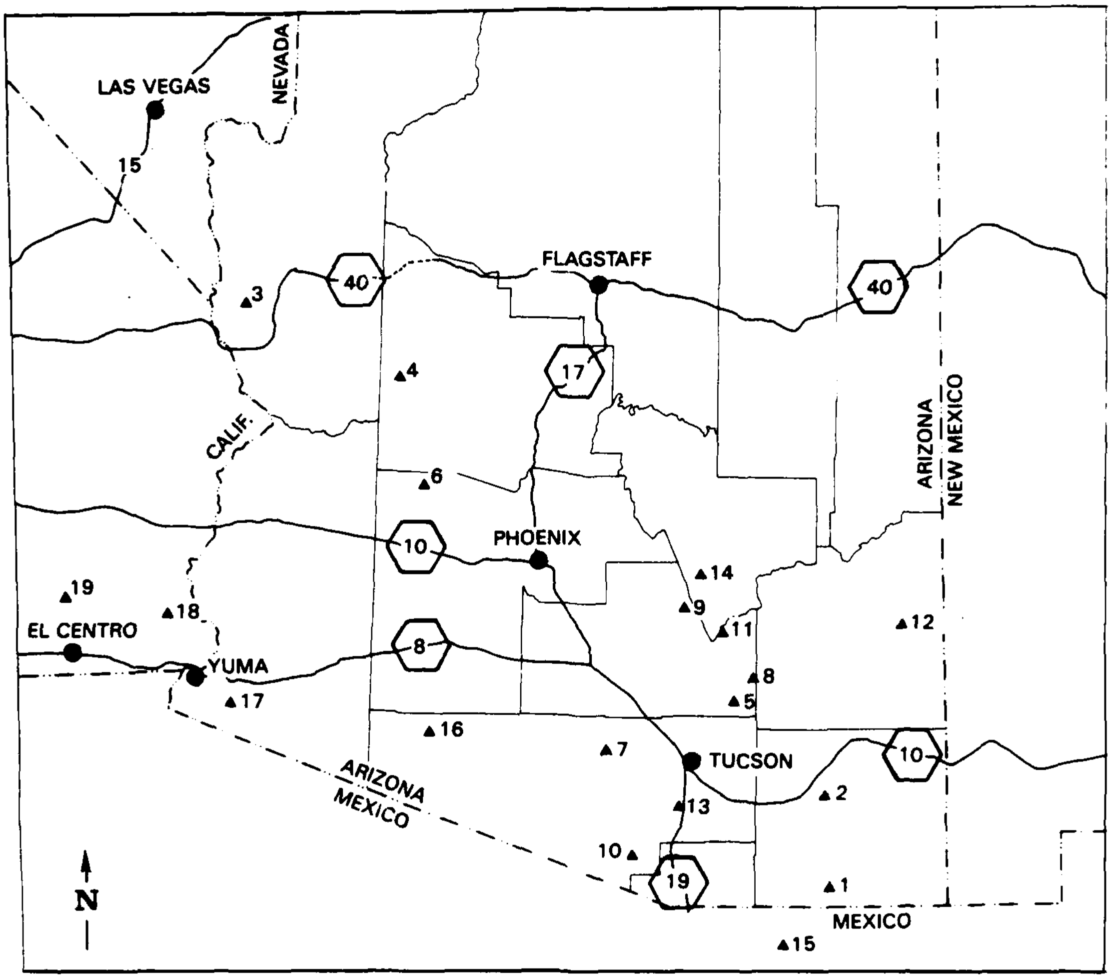
Gravity and ground magnetic geophysical field studies were accomplished at MCAS, Yuma, and south and east into R-2301 West in May 1984. A total of 250 gravity and ground magnetic data stations were set using a Wild theodolite and wide faced surveying rods. The stations were set mainly along existing roads at an average interval of 1000 feet.

Observed gravity was measured at each station using a LaCoste and Romberg gravity meter (Model G - No. 717) in a series of 4-hour drifts with checkpoints. The survey was tied to USGS Bench Mark R257 located along an irrigation canal about 1.2 miles north of the main gate to MCAS, Yuma. Raw station data were then reduced with the 1967 latitude correction assuming a reduction density of 2.40 g/cm^3 (Reference 31). Terrain corrections were taken in the field to a distance of 175 feet (Zone C of a Hammer chart in Reference 31) and then with a computer through approximately 72,000 feet (Zone M).

Appendix Table A-4 lists the results of this gravity survey in tabular form while Figure 15 shows the results in the form of a complete Bouguer gravity map, plotted using a reduction density of 2.40 g/cm^3 and contoured on an interval of 1 mgal. The map shows that

TABLE 3. Analysis of Radium Hot Springs Water Constituents in Parts per Million (ppm).

SiO_2	101.0
Fe and Al oxides	3.9
Ca	162.0
Mg	None
Na	746.0
K	17.0
Cl	740.0
SO_4	898.0
CO_2	None
Bicarbonates	73.0
Total dissolved solids	2804.0



▲SITE	DEPOSIT	AGE MYBP
1	BISBEE	163
2	JOHNSON CAMP	74.1
3	ITHICA PEAK	72
4	BAGDAD	71
5	SAN MANUEL	67
6	VULTURE MOUNTAINS	67
7	SILVERBELL	67 – 63
8	COPPER CREEK	65.8
9	RAY	63
10	ESPERANZA	62
11	CHRISTMAS	62
12	MORENCI	62 – 55
13	PIMA – MISSION	60
14	MIAMI	60 – 56
15	CANANEA	59
16	AJO	40 – 35 (?)
17	FORTUNA	45
18	MESQUITE	39 – 32
19	SALTON SEA	PRESENT

FIGURE 14. Ages of Mineral Deposits and Magmatic Events, Southern Arizona-Southwestern California.

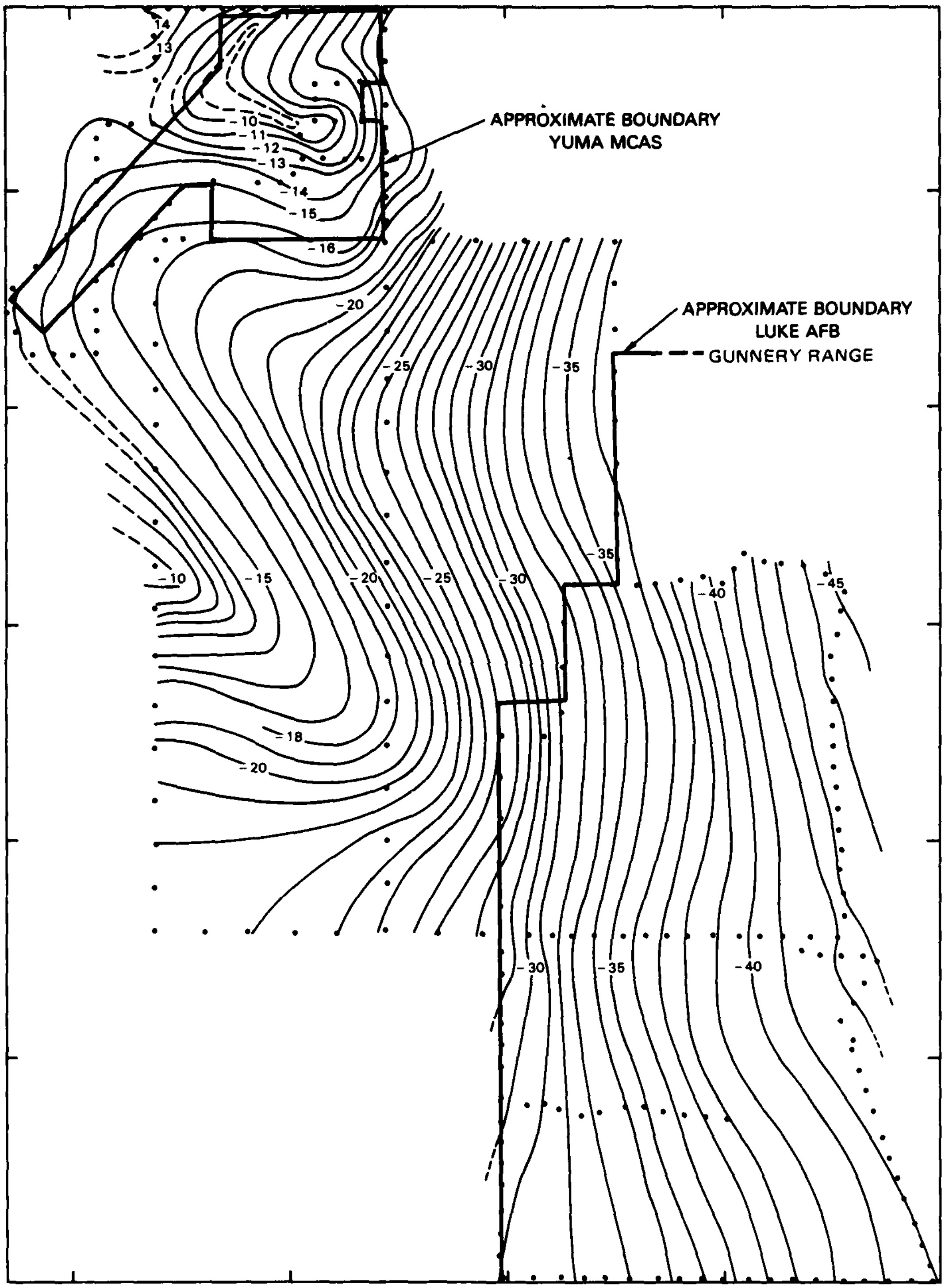


FIGURE 15. Local Complete Bouguer Gravity Map.

MCAS, Yuma, is located on a local gravity maxima, probably corresponding to what Reference 7 calls the Yuma anomaly (Figure 7). South of MCAS, Yuma, the gravity quickly falls from northwest to southeast at an almost constant 6 mgal per mile gradient toward the Fortuna Basin. In the central map area, another relative gravity high is emerging that probably corresponds to the Mesa anomaly of Reference 7.

The ground magnetic survey was taken in conjunction with the gravity survey with data being gathered using a Geometrics magnetometer. No recording base station was used. The data were smoothed by repetitive readings from base stations and checkpoints. Appendix Table A-4 contains data on the ground magnetic survey from MCAS, Yuma, and vicinity.

Figure 16 shows the plotted results of the ground magnetic survey contoured on an interval of 20 gammas. The most prominent feature on the map is the large magnetic high located in the extreme north portion of the area. This high corresponds to the Yuma anomaly gravity high seen on Figures 9 and 15. The Mesa gravity anomaly also has a localized high ground magnetic signature.

The coincidence of overlapping gravity and magnetic highs for both the Yuma and the Mesa anomalies adds credence to the statement made in Reference 7 that both anomalies are caused by near-surface basement rocks. East of these anomalies the gravity tends to indicate a thickening series of sediments into the Fortuna Basin. However, ground magnetic values decrease toward the Fortuna Basin, then increase slightly near the east end of the mapped area. This seems to indicate some sort of structural complexity in this area, which may be explained by a less dense rock type having a localized (?), higher magnetic susceptibility. That this is due strictly to sediments is unclear, but such a phenomenon seems unlikely.

One other point worth mentioning is the possibility of some sort of linear structure (fault?) in the southern portion of the ground magnetic map. Its magnetic signature is very subtle and may only be due to poor station density. The feature follows the 49200-gamma contour line roughly east-to-west. Such a feature may be important in further geothermal work because it might provide a conduit for deep-seated geothermal fluids from the Fortuna Basin. This feature is not seen on the complete Bouguer gravity map.

GEOTHERMOMETRY

Quantitative chemical geothermometers and mixing models are significant tools to the geothermal explorationist as they can indicate current probable minimum subsurface temperatures. Interpretation is based on an understanding of temperature-dependent rock-water reactions at depth and is easiest in an area where the waters available for analysis come fairly directly from the source (such as areas with widespread hot and warm springs activity). Geothermometry is difficult to apply (with any reliability) in the Yuma area because the waters that are available are primarily, or almost exclusively, from the upper ground-water reservoir (the production reservoir). These waters have been subjected to extensive mixing through ground-water movement and contamination by percolating surface waters from agricultural uses; and, as a result, any natural chemical balance in the waters has been disturbed.

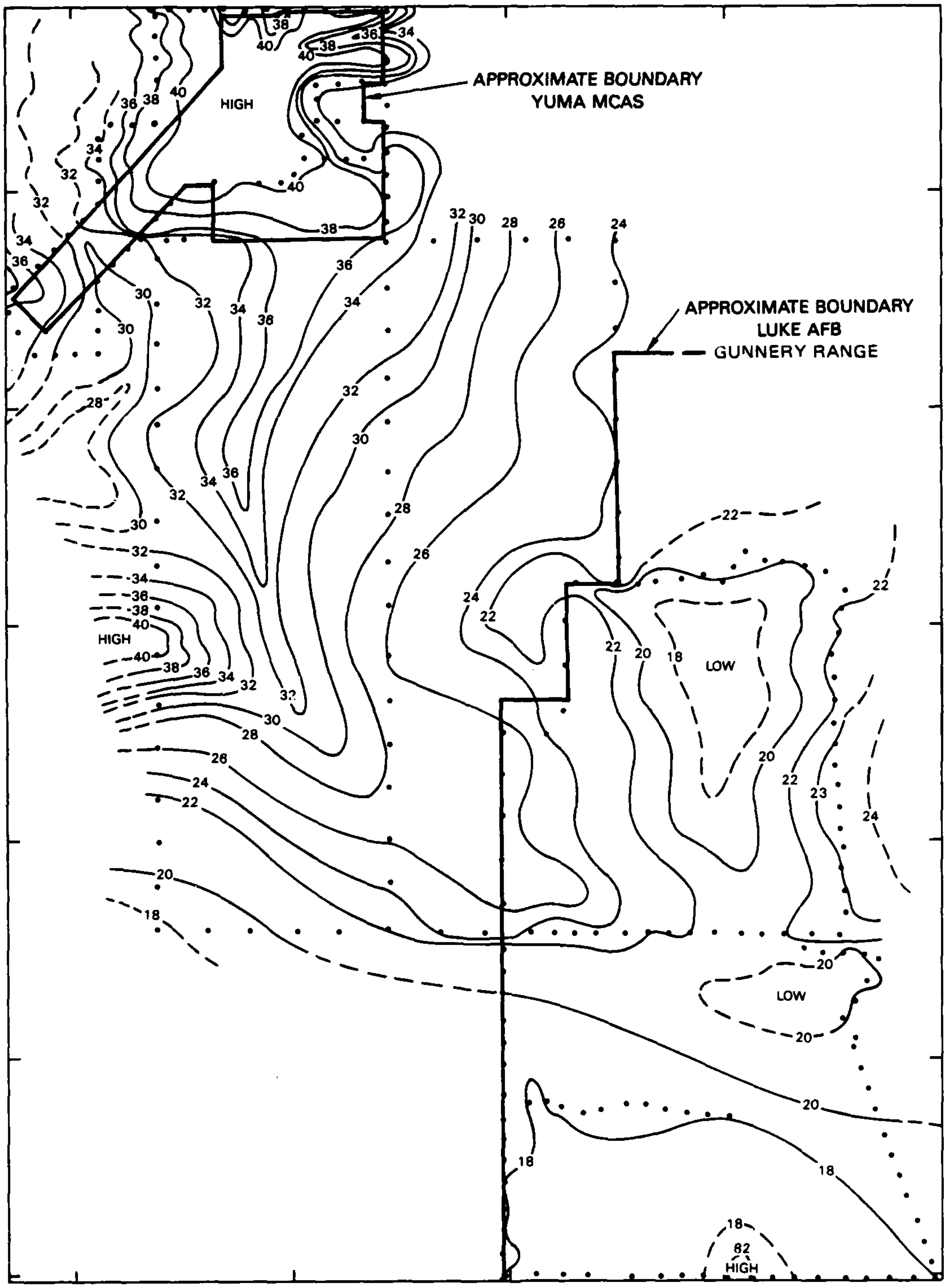


FIGURE 16. Local Ground Magnetics Map.

The results of geothermometric calculations of the Radium Hot Springs waters (from Table 3) are given in Table 4. The major geothermometers indicate maximum heat-source temperatures in the range of 92.7 to 151.1°C (198.8 to 304.0°F) for these waters. No mixing models were attempted; but since these springs emanated from the river mud flats next to the granitic outcrop, some mixing of the geothermal waters and the river waters should be expected. The magnesium correction for the sodium-potassium-calcium geothermometer does not apply. The sodium-lithium geothermometer was not applied because the lithium content of the sample was not determined. Amorphous silica figures are disregarded because they tend to be consistently anomalous in the Basin and Range.

In the 1973 study of the geohydrology of the Yuma area, Olmstead and others published a map of the temperature of ground water in the coarse gravel zone of the upper aquifer (Figure 12). Data for this map came from shallow temperature measurements of nearly 500 wells. Several "warm anomalies" were noted, particulary in the Yuma Mesa and Upper Mesa areas. The authors of that study believed that most of these anomalies were related to faults or fault zones, such as the Algodones fault, but that "some anomalies may reflect hot zones in the pre-Tertiary crystalline rocks that are not related to faulting." (So far as we have been able to determine, little work has been done in trying to identify chemical geothermometric anomalies correlative with these "warm anomalies." As stated earlier, mixing and contamination is a major problem when working with the upper aquifer waters; but if "significant" temperature differences can be distinguished, perhaps--with the right set of assumptions--slight differences in water chemistry can lend themselves to valid anomaly interpretation.)

Figure 17 shows a more recent map of southwestern Arizona and southeastern California noting the locations of warm wells and springs used in a delineation of areas with geothermal potential based on water temperature and geothermal gradient. This map is modified from References 32 and 33. Table 5 lists the wells and springs shown on the map.

The shaded area south and east of Yuma is known as the Mesa anomaly and is defined as favorable for discovery and development of low-temperature (lower than 100°C) geothermal resources. The wells show temperatures higher than 50°C and temperature gradients of 50°C/km or lower. The total amount of data on which this area was defined is not extensive and does not imply that thermal waters may be found everywhere within the area, nor do the boundaries represent certain knowledge of the areal extent of the geothermal resources.

TABLE 4. Chemical Geothermometry Analysis of Radium Hot Springs Waters.

Geothermometer	Temperature, °C (°F)
Quartz conductive	151.1 (304.0)
Chalcedony conductive	111.1 (232.0)
Quartz flash	133.2 (271.8)
Amorphous silica	17.4 (63.4)
Na-K modified	116.3 (241.3)
Na-K-Ca (B = 4/3)	92.7 (198.8)

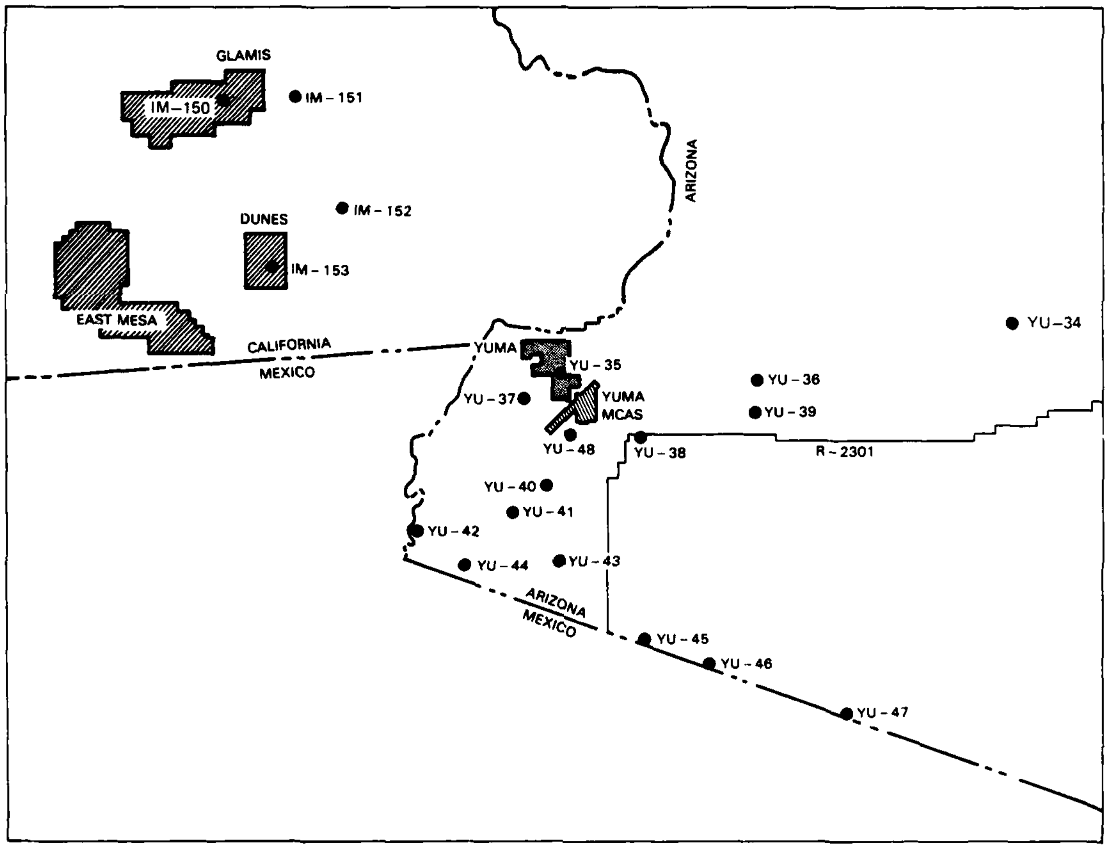


FIGURE 17. Location of Warm Wells and Springs in the Yuma Area.

TABLE 5. Data for Thermal Wells and Springs, Yuma, Arizona, and Vicinity.

Well no.	Temperature, °C (°F)[a]	Total dissolved solids, ppm	Depth, m (ft)
YU-34[b]	60 (140)	2240	...
YU-35	34 (93)	...	735 (2411)
YU-36	36 (97)	4440	91 (299)
YU-37	40 (104)	1536	...
YU-38	36 (97)	...	707 (2320)
YU-39	35 (95)	...	365 (1197)
YU-40	34 (93)	...	231 (758)
YU-41	52 (126)	...	1835 (6020)
YU-42	38 (100)	...	896 (2940)
YU-43	35 (95)	...	230 (755)
YU-44[c]	138 (280)	...	3216 (10,551)
YU-45	36 (97)	626	106 (348)
YU-46	35 (95)	...	98 (322)
YU-47	38 (100)	...	366 (1201)
YU-48[d]	53.4 (128)	...	747 (2450)
IM-150	70 (158)	...	207 (679)
IM-151	30 (86)	...	213 (699)
IM-152	37 (99)	...	210 (689)
IM-153	100 (212)	...	107 (351)

[a] Bottom-hole temperature for wells.
[b] Radium Hot Springs (dry).
[c] Exxon Federal #1, also logged by Geothermal Program Office, GEOPROF, August 1985.
[d] Bradco #2 (?) logged by GEOPROF, August 1985.

Included in Figure 17 and in Table 5 are two deep oil and gas exploration wells, Exxon Federal #1 and Bradco #2 (?), logged by GEOPROFF personnel in August 1985. Both wells were logged to 2450 feet (limit of equipment). Efforts were made to locate and log other deep wells in the area, but none were found to be accessible.

The authors obtained a geothermal gradient of 2.7°F/100 ft for the upper section (2450 feet) of Exxon Federal #1. This is in agreement with the previously published gradient of 2.2°F/100 ft, which was based on a single bottom-hole temperature measurement. Because the top of the Bouse Formation is over 3000 feet deep in this part of the San Luis Basin, the thermal log did not get below the fresh ground-water reservoir.

The Bradco well is a recent wildcat oil well and had not been previously temperature logged. This well logged-out with a slightly better gradient (3.5°F/100 ft). This is still well within the thermal-gradient range for the Basin and Range province. Again, we probaby did not get below the Bouse Formation.

GEOTHERMAL POTENTIAL

Stone and Witcher (Reference 3) consider the proximity of the Yuma area to the many known geothermal anomalies in the Salton Trough area, as well as the similarities in structure of the two areas, to be sufficient to make Yuma a favorable target for geothermal exploration even though surface thermal features are unknown in this area.

Using some previous thermal gradient work of Stone and the shallow ground-water temperature map of Olmstead and others (Figure 11 of this report), Stone and Witcher note the zones of anomalously warm ground water in the area and a geothermal-gradient anomaly along the northwest-trending Algodones fault system, which suggest the occurrence of hydrothermal systems. They conclude that they "expect that potential geothermal resources in the Yuma area, when found, will be below the Bouse Formation [sedimentary strata] or in basement rocks and that the fluids are likely to have high TDS [total dissolved solids]."

In his presentation of a geothermal development plan for Yuma County, White (Reference 4) identifies (or infers) four potential low-temperature resource areas (<90°C) and two intermediate-temperature resource areas (90 to 150°C) using the USGS definition of a possible geothermal resource area as having water temperatures 10°C greater than the mean annual air temperature and temperature gradients greater than 25°C/km (1.4°F/ft). The only one of these sites that is located in our area of interest is the Mesa anomaly in the Fortuna Basin (Figure 17).

White speculates that active tectonism in the Salton Trough/Gulf of California system periodically reactivates fracture permeability in the basement rock along the Algodones and associated faults (Reference 4). This allows for convective heat transfer to shallow depths and, therefore, the above-normal gradients in the area of the Mesa anomaly could be the result of a high conductive heat flow.

Poluianov and Mancini in the most recent evaluation of the geothermal potential of the Yuma area reached similar, but somewhat more pessimistic, conclusions (Reference 5). They assumed two general types of geothermal systems for their evaluation: the hot impermeable rock and the convective hydrothermal systems. The convective systems were modeled after the Salton Trough geothermal areas. (They could find no evidence for the existence of either a geopressured system or of a magma pool close to the surface.)

The basis for their evaluation was a statistical methodology called the Analytical Hierarcy Process (AHP). According to Reference 5, this technique "structures a system and its environment into mutually interacting parts and then by rating the 'interactions' of these parts on each other and on the entire system (e.g., the geothermal system), using a knowledge base and rules, the technique enables the user to evaluate the system." They further stated that they do not believe that AHP is meant replace the more traditional methods of the explorationist, but that its use can document the interactions or influences of various factors, especially with a complex system.

In terms of electricity production and district heating and cooling using geothermal brines, they concluded that the City of Yuma and MCAS, Yuma, are located in an area of very low (less than 50°C) geothermal resources and that higher temperature resources are both deep and remote from this relatively high energy demand area.

They did feel, however, that the Fortuna Basin (far western portion of the R-2301 Range) is "likely to have brines in excess of 170°C in its deeper regions." (They state that 170°C is a minimum temperature for binary electricity production.) In addition, they noted that some potential may exist for hot dry rock (HDR) exploration in the Yuma/MCAS area, but that the database is quite sparse. (We should note that despite these statements, the Russians and the Chinese are quite successful at producing electricity with geothermal temperatures as low as 90°C.)

(We should also note that these authors identified two other areas inside the R-2301 Gunnery Range that they felt may have hot dry rock potential, these being the most recent volcanic areas of Sierra Pinacate and Cabeza Prieta. Because of inaccessibility of these areas, a lack of geophysical and other data, and the questionable viability of HDR technology in this environment, we did not include these areas (east of the Gila and Tinajas Altas Mountains) in our evaluation of the geothermal potential of the R-2301 Range.)

DISCUSSION AND CONCLUSIONS

When examining potential exploration models for the Yuma area, we find that because the area is in a transition zone between two distinct geologic provinces, several very different geothermal resource models are possible. To adequately distinguish these models, a classification scheme of some kind is necessary. Sanyal and others (Reference 34) described a classification scheme that is oriented toward the analysis of electric log response in exploration and development wells. We have taken this classification, simplified it slightly, included some components of geothermal systems that cannot be gauged in a drill hole, and have found the resulting scheme to be a handy framework on which to base our evaluation of the geothermal potential of MCAS, Yuma, and the westermost section of R-2301 West.

The classification scheme we used, given in Table 6, should not be viewed as a rigid and complete characterization of possible geothermal systems. It is strictly a framework for comparison and discussion. Although we attempt to be impartial in our listing of relevant characteristics, biases based on an understanding of geothermal systems within geologic provinces tend to creep unavoidably into the evaluation and may be reflected in the models described. Obviously, many of the characteristics listed in Table 6 include similar or related items and the outline could be expanded. This will be done when the working models are described further on.

Based on our understanding of the general geology of the Yuma area, we established a number of "conceivable" models for the occurrence of geothermal resources at MCAS, Yuma, and R-2301 West. These ranged from a sedimentary-type occurrence of low-to-moderate temperature and shallow-to-moderate depth through a deep hot water occurrence in brecciated and hydrothermally altered metamorphic or crystalline igneous rock to a dry metamorphic or crystalline igneous rock with low intergranular and vuggy porosity occurring below about 2500 feet.

As we gathered and evaluated data on the geothermal potential of the area, we further refined our models and established four working models.

TABLE 6. Geothermal Resource Classification Components.

I. Geologic Province
  A. Basin and Range
  B. Salton Trough

II. Fluid Phase and Temperature
  A. Steam
  B. High-temperature water (>149°C (>300°F))
  C. Low-to-moderate-temperature water (30 to 149°C (86 to 300°F))
  D. Dry

III. Lithologic Type
  A. Sedimentary
  B. Metamorphic and crystalline igneous
  C. Volcanic ash, tuff
  D. Breccia and hydrothermally altered

IV. Pore Geometry
  A. Sedimentary intergranular porosity
  B. Fracture or vuggy porosity

V. Salinity and Fluid Chemistry
  A. Low salinity (<5000 ppm TDS)
  B. Moderate-to-high salinity (5000-100,000 ppm TDS)
  C. Hypersaline (>100,000 ppm TDS)
  D. Dry

VI. Heat Source
  A. Near-surface heat source
  B. Normal thermal gradient

VII. Depth to Resource
  A. Shallow (<2500 ft)
  B. Moderate (2500 to 7000 ft)
  C. Deep (>7000 ft)

Resource Model 1 occurs in a Salton Trough-type environment. It is a high-temperature, moderate-to-high-salinity fluid (water) in a sedimentary host (possibly tuffaceous) with primarily intergranular porosity (possibly some fracture or vuggy porosity depending on the depth of occurrence and the degree of diagenesis/metamorphosis that has taken place). This model has a near-surface heat source (possibly remote from the site of inquiry with heat transmitted by regional ground-water flow or along fault-induced channelways). The occurrence must necessarily be at moderate depth or deeper (>2500 feet). This model is directly related to a spreading center/transform fault environment.

Resource Model 2 is similar to Model 1. However, the fluid is low-to-moderate-temperature water with low-to-moderate salinity, the porosity is entirely sedimentary intergranular, and the resource may occur in the valley fill of an intermontane basin and be associated with a basin and range extensional environment (or a period of relaxation in a deep-seated compressional episode) as well as being related to the classic Salton Trough environment.

The exploration clues are likely to be more subtle for Model 2 than they are for Model 1. Although the resource is likely to be nearer the surface, the lower temperature and salinity make thermal gradient, electro-chemical, and geothermometry indicators difficult to distinguish from background values, especially in the Yuma area where extensive ground-water mixing has taken place.

Resource Model 3 is set in the Basin and Range geologic province. It shows a low-to-moderate-temperature fluid (water) of low-to-moderate salinity occurring at shallow-to-moderate depth in a metamorphic or crystalline igneous host rock. The reservoir porosity is entirely vuggy coupled with secondary fracturing. The fracturing may be very localized and intense (breccia). Heat is transferred from a near-surface heat source into the reservoir by hydrothermal convection. Low-to-moderate-temperature hydrothermal alteration is likely and may take the form of warm springs and active (or recent) epithermal mineral deposits.

Resource Model 4 is similar to Model 3 except that the fluid is high temperature (>149°C) with moderate salinity. The host rock is likely to be intensely fractured with pronounced zones of hydrothermal alteration, and although the heat source is likely to be near-surface, depth to the resource is in excess of 2500 feet.

Some may prefer to view these as essentially two models, one being a Salton Sea type in a fractured metamorphic or crystalline igneous host rock. We, however, have chosen a middle ground between models that may be too simple to be useful and those that may be too descriptive and therefore restrictive in their application.

The geothermal explorationist has a wide array of tools and techniques available to him in the assessment of geothermal resource potential of an area. However, these tools have varying applicability depending on the resource model sought. Table 7 lists several exploration techniques commonly applied to the search for geothermal energy and ranks them numerically by their applicability to the two geologic provinces of our models. (The ranking is not based on the order in which the techniques should be applied. Order of application is often based on such things as availability of existing data, land position, management biases, and monetary constraints.)

As we balance the resource models against the geologic data that have been gathered on the Yuma area (particularly MCAS, Yuma, and R-2301 West) and the wide array of applicable assessment tools, we find that there are a number of components of the models for which the data are discriminatory and others for which additional data are needed. In light of the available data, we can best assess the geothermal potential of the area in terms of Resource Models 2 and 3.

TABLE 7. Regional Applicability of Exploration/Assessment Technique.
Adapted from Reference 35.

Technique	Salton Trough	Basin and Range
Thermal-gradient drilling[a]	1	1
Gravity	2	7
Electrical resistivity methods	3	4
Seismic methods	4	5
Well logging	5	8
Fluid chemistry	6	3
Air photogeology	7	6
Magnetics	8	10
Surface geologic mapping	9	2
Age dating	10	9
Remote sensing	11	11

[a] Includes hydrologic data gathering.

Model 2 is a low-to-moderate temperature, low-to-moderate salinity fluid occurring entirely in a sedimentary host at shallow-to-moderate depth on the edge of the spreading center/transform fault environment with possible additional structural controls imposed by the intersection of the northwest trending San Andreas fault system and the pre-existing east-northeast trending buried structures of the Gila lineament (Salton Trough province with probable older Basin and Range related influences). Available temperature gradient data indicate the possibility of a low-to-moderate-temperature resource in the deeper sediments. We agree with Stone and Witcher (Reference 3) in that a viable resource is unlikely above the primary aquiclude in the basin, the Bouse Formation, particularly in the agriculturally developed areas. However, little information is available for the southeast corner of the Fortuna Basin. This area may be far enough removed from the well-developed part of the basin (and therefore, from the ground-water contamination and mixing in the shallow aquifer) to offer some potential for a shallower resource than might be expected on the western side of the basin or in the San Luis Basin to the west.

Much of the existing geophysical data support this model. In reviewing this work (particularly the gravity and magnetic surveys), we find several things to be evident.

The San Andreas trends are seen by both surveys as elongate northwest-trending basins separated by moderate ridges, indicating en echelon step faulting typical of a rift environment. In the gravity surveys, this pattern is more apparent to the southeast of Yuma than to the northwest where the trend enters the Imperial Valley-Salton Sea area and the strong geothermal anomalies overprint the structural pattern with gravity highs. In the Imperial Valley geothermal areas these faults often act as conduits for the upward movement of geothermal fluids. The same is probable for the Yuma area.

There is some evidence that many of the lineaments in Arizona tend to control the location of Quaternary volcanic systems and that the major lineament systems correlate reasonably well with known geothermal areas and occurrences. In the southwestern part of the state, Radium Hot Springs, Agua Caliente, and the Gila River known geothermal

resource area are associated with the Gila trend; while in Sonora, Mexico, just south of the study area, the Quaternary Pinacate lava field lies at the three-way intersection of a San Andreas lineament (the Algodones fault), the Pinacate system, and a west-northwest system lying just south of the Arizona-Sonora border. The points of intersection of two or more of these geophysical trends are areas of potential weakness in the basement rock. Identification of them may serve as an exploration guide to buried potential geothermal resource targets.

By projecting the Gila trend southwest through the San Andreas trends, we note that the Yuma basement high (on which MCAS, Yuma, sits) is at the intersection of these trends. Several of the warm water wells in the Yuma basin are also in this trend, including Exxon's Federal #1 well (YU-44) near the Mexican border. This well is 3216 meters deep and has a published thermal gradient of 40°C/km. When we logged the upper 747 meters of the hole in 1985 we obtained a gradient of 43°C/km, which is within the thermal gradient range for the Basin and Range, but which may indicate locally elevated temperatures.

We also believe that some slight potential exists for a geothermal resource patterned after Model 3 at MCAS, Yuma (Yuma basement high), in the boundary high area, and in the western Tinajas Altas Mountains. Resource Model 3 shows a low-to-moderate-temperature fluid occurring at a shallow-to-moderate depth in a fractured metamorphic or crystalline igneous host rock.

The available evidence for this model is indirect and circumstantial. These highs are composed of pre-Tertiary igneous and metamorphic rocks that have been left "standing" for some reason while the areas around have dropped (or been eroded) substantially and have been buried beneath thick sedimentary sequences. The highs may represent erosion-resistant hills supported by a framework of hydrothermal veins and alteration. Past mineralization indicates that shallow-to-moderate depth hydrothermal systems have been prevalent in southwestern Arizona and southeastern California, and the geothermal occurrences on the Gila trend and the scattered Quaternary and Recent volcanism indicate that the hydrothermal processes have not necessarily ended.

Additional discriminatory data can be gathered along several avenues of geothermal exploration. These avenues are discussed below.

A resistivity survey of the MCAS, Yuma, and vicinity aimed at looking for lower resistivity ground water with a geothermal component would probably meet with limited success. In the Yuma basin there is one good aquiclude, the Bouse Formation. The Bouse Formation is composed of Pliocene marine sediments and separates the older nonmarine sediments and related rocks from the younger (Pliocene to Recent) alluvial deposits that make up the ground-water reservoir. In the southwest part of the area (near San Luis) the Bouse Formation is intersected below 3000 feet. The formation rises gently toward the north and northeast and may be as shallow as 350 feet under the Colorado River at Yuma. It is not present across much of the Yuma basement high, but there may be remnants of it in the deeper "basins" of the basement across this high. The MCAS, Yuma, is situated over a large "basin" in the basement high.

If the Bouse Formation forms an aquiclude beneath the MCAS, Yuma, geothermal leakage could be hidden. However, all the sedimentary cover over the high is probably part of the ground-water reservoir and, because of the extensive mixing that takes place in the

ground-water reservoir in the Yuma area, it is likely that no geothermal plume large enough to be detected with a resistivity survey would exist.

The same is not necessarily true for the Fortuna Basin section of R-2301 West. A deep resistivity survey around the thermal wells in this area might help define the anomaly.

Detailed geologic mapping of surface outcrops in the Yuma area is recommended. This is particularly true for the basement outcrops of the Yuma and Boundary highs and the west side of the Gila and Tinajas Altas Mountains. The survey would be oriented toward mapping and sampling evidence of recent hydrothermal activity (spring terraces, hydrothermal alteration, etc.) and relating it to other hydrothermal mineral occurrences in the area. Trace-element and isotope studies may be included with this field effort.

Trace-element and ion analyses of ground water--especially ground water below the Bouse Formation--could be beneficial. As stated earlier, ground-water mixing in the Yuma basin is extensive, especially in the upper aquifer. In addition, water sampling and analysis in the area is oriented toward water quality rather than toward geothermal exploration. As a result, geochemistry has been difficult to apply to our study. If enough wells could be found that would give us a statistically reasonable sample population and a good areal distribution throughout the area of investigation, trace elements/ionic species could be very useful for both geochemistry and geothermometry. The trace elements of interest would be arsenic, boron, lithium, mercury, and strontium. A controlled program of selective deep-well sampling, analysis of geothermal indicators, and careful interpretation could help to understand the mixing problem.

An examination of aerial and satellite photography of the area could also be beneficial. We would be looking for conformation of regional structural trends as well as any local anomalies in these trends that could enhance the formation of a geothermal resource.

Thermal-gradient drilling is an important part of a total geothermal-resource assessment as it is the most direct indicator of the resource. A combination of shallow and deep drilling beneath the MCAS, Yuma, could add substantially to our understanding of the geothermal potential. However, at this time the cost of drilling, particularly deep thermal-gradient drilling in the Fortuna Basin, is not justified in light of the potential resource indicated.

While the Fortuna Basin offers us a certain freedom of movement in the area for data gathering, we do not believe that any "regional" studies will substantially improve our options at MCAS, Yuma. The problem is one of land position. The MCAS, Yuma, is small--a little more than 5 square miles with little room to spare. With the above mentioned programs (excluding drilling), we may be able to substantiate the potential for a geothermal resource in the MCAS, Yuma, area, but this will not improve our land position. For deep drilling into the Yuma anomaly at MCAS, Yuma, only one drill site is likely, this being in the southeast corner of the station, away from the runway and the operations center.

Specifically, based on available field data, it is the belief of the authors that MCAS, Yuma, does not represent a sufficient potential to warrant further exploration efforts at this time. By the same token, the authors do believe that sufficient potential for geothermal resources exists in the western portion of the Luke-Williams Gunnery Range (R-2301 West) to

justify further exploration. To this end, we recommend that the following steps be taken to better define this potential:

1. Conduct a detailed geologic reconnaissance of the Fortuna Basin and surrounding area. This effort should include detailed geologic mapping, chemical and isotopic analysis of ground-water and rock samples, and photogeologic analysis as outlined previously.

2. Conduct deep geophysical surveys of selected portions of the basin. These surveys will be sited based on the geologic reconnaissance and will probably include electrical resistivity and some type of telluric investigation (MT, AMT, etc.). The application of deep seismic techniques would help define the buried structure of the basin, but this option is relatively expensive and should be reserved as a lower priority item.

3. Because of the lack of subsurface data points in and around the Fortuna Basin, a drilling program of several shallow thermal-gradient holes will probably be necessary. This program will be of multiple benefit in that it will provide better definition of the estimated thermal anomalies; provide clean, current, and accessible ground-water sampling sites; and provide subsurface geologic data on which to focus the geophysical investigations.

At the conclusion of these steps, the geothermal potential of the area will be reevaluated to determine if a deep test well is warranted.

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Appendix
REGIONAL DATA

TABLE A-1. Potassium-Argon Dates for Rock Samples, Yuma County and Vicinity.
Data taken from Reference 16.

Location	Rock type	Date, MYBP
2	pegmatite	1400 ± 45
4	gneiss	1300 ± 40
19	granite	577 ± 17
21	granite	167 ± 4
25	granite	140 ± 4
33	amphibolite	70.3 ± 2.9
36	metamorphic	67.1 ± 1.4
38	granodiorite	66.5 ± 3.6
39	granite porphyry	66.0 ± 2.2
41	quartz schist	64.6 ± 1.5
45	orthogneiss and schist	54.9 ± 1.2
47	quartz monzonite	55.0 ± 1.2
48	granite	53.2 ± 1.6
49	granite	53.1 ± 1.3
50	diorite	52.8 ± 1.1
51	granite	52.5 ± 1.3
52	quartz monzonite	51.0 ± 1.1
55	granite	47.5 ± 1.0
56	granodiorite	47.0 ± 1.0
57	granite	44.1 ± 1.3
60	rhyolite tuff	30.1 ± 1.0
62	diorite dike	25.4 ± 1.6
66	basaltic andesite	25.8 ± 1.6
67	hornblende andesite	25.4 ± 1.5
68	gneissic quartz monzonite	25.33 ± 0.54
72	latite ash-fow tuff	23.7 ± 0.7
73	basalt	23.7 ± 0.6
74	rhyolite ash-flow tuff	23.6 ± 0.6
78	rhyolite tuff	22.5 ± 0.7
79	basalt	21.68 ± 0.57

TABLE A-1. (Contd.)

Location	Rock type	Date, MYBP
82	ltrachyte (ultrapotassic)	21.03 ± 0.54
83	basalt	20.9 ± 0.53
84	andesitic basalt tuff	20.7 ± 0.5
93	latite intrusion (dike)	19.98 ± 0.58
98	rhyolite tuff	19.41 ± 0.47
105	basaltic andesite	18.31 ± 0.42
110	andesitic intrusive	18.81 ± 0.52
113	basalt	17.24 ± 0.43
115	granodiorite	16.46 ± 0.54
116	basalt	16.28 ± 0.40
117	basaltic andesite	16.16 ± 0.95
118	basaltic andesite	16.14 ± 0.75
119	andesite	16.12 ± 0.41
127	basalt	14.00 ± 0.32
129	trachyte	13.9 ± 0.3
131	andesite	13.35 ± 0.32
137	basalt	10.49 ± 0.41
138	olivine basalt	10.02 ± 0.35
139	basalt	9.62 ± 0.38
140	basalt	9.55 ± 0.38
142	basalt	8.52 ± 0.29
147	vitric tuff	5.47 ± 0.20
148	basalt	5.4 ± 1.0
152	basalt	3.19 ± 0.11
153	basalt	2.17 ± 0.25
155	basalt	1.72 ± 0.46
160[a]	basalt	3.0 ± 0.1
161[b]	basalt	0.461 ± 0.036

[a] Data taken from Reference 17.
[b] Data taken from Reference 10.

TABLE A-2. Thermal Gradient Log, Exxon Federal #1.

Depth, ft	Temp., °C	Depth, ft	Temp., °C	Depth, ft	Temp., °C	Depth, ft	Temp., °C
G.L.	36.5	625	29.1	1250	32.5	1875	38.9
25	28.5	650	29.2	1275	32.7	1900	39.2
50	28.4	675	29.2	1300	32.9	1925	39.5
75	28.2	700	29.3	1325	33.1	1950	39.7
100	28.2	725	29.4	1350	33.4	1975	40.0
125	28.2	750	29.5	1375	33.6	2000	40.3
150	28.3	775	29.5	1400	33.8	2025	40.6
175	28.3	800	29.6	1425	34.1	2050	40.8
200	28.4	825	29.6	1450	34.3	2075	41.1
225	28.4	850	29.7	1475	34.6	2100	41.4
250	28.3	875	29.8	1500	34.8	2125	41.7
275	28.3	900	30.0	1525	35.1	2150	42.0
300	28.3	925	30.1	1550	35.1	2175	42.2
325	28.4	950	30.3	1575	35.5	2200	42.5
350	28.4	975	30.4	1600	35.8	2225	42.8
375	28.5	1000	30.6	1625	36.1	2250	43.1
400	28.6	1025	30.7	1650	36.4	2275	43.3
425	28.6	1050	30.9	1675	36.6	2300	43.6
450	28.7	1075	31.1	1700	36.9	2325	43.9
475	28.8	1100	31.3	1725	37.1	2350	44.2
500	28.8	1125	31.5	1750	37.4	2375	44.4
525	28.8	1150	31.7	1775	37.7	2400	44.7
550	28.9	1175	31.9	1800	38.0	2425	45.0
575	29.0	1200	32.1	1825	38.3	2450	45.3
600	29.0	1225	32.2	1850	38.6		

TABLE A-3. Thermal Gradient Log, Bradco Wildcat Well #1.

Depth, ft	Temp., °C	Depth, ft	Temp., °C	Depth, ft	Temp., °C	Depth, ft	Temp., °C
G.L.	41.6	625	32.0	1250	38.5	1875	45.1
25	39.5	650	32.3	1275	38.7	1900	45.5
50	36.8	675	32.5	1300	38.9	1925	45.9
75	34.3	700	32.7	1325	39.1	1950	46.3
100	25.6	725	33.0	1350	39.3	1975	46.7
125	25.2	750	33.2	1375	39.5	2000	47.0
150	25.4	775	33.6	1400	39.8	2025	47.4
175	25.4	800	33.9	1425	40.0	2050	47.8
200	25.5	825	34.3	1450	40.2	2075	48.2
225	25.5	850	34.5	1475	40.4	2100	48.5
250	25.4	875	34.8	1500	40.6	2125	48.9
275	25.4	900	35.1	1525	40.9	2150	49.3
300	25.5	925	35.3	1550	41.1	2175	49.6
325	25.6	950	35.6	1575	41.3	2200	50.0
350	25.8	975	35.8	1600	41.5	2225	50.4
375	26.0	1000	36.1	1625	41.8	2250	50.7
400	26.4	1025	36.3	1650	42.0	2275	51.1
425	27.0	1050	36.5	1675	42.2	2300	51.4
450	27.6	1075	36.8	1700	42.4	2325	51.8
475	28.4	1100	37.0	1725	42.8	2350	52.1
500	29.3	1125	37.2	1750	43.2	2375	52.5
525	30.0	1150	37.5	1775	43.6	2400	52.8
550	30.7	1175	37.7	1800	44.0	2425	53.1
575	31.2	1200	38.0	1825	44.4	2450	53.4
600	31.5	1225	38.2	1850	44.7		

TABLE A-4. Gravity and Magnetics Survey Data.

Station ID	Latitude[a]	Longitude[a]	Elevation, ft	Gravity,[b] mgal	Complete Bouguer anomalies,[c] g/cm³			Corrected magnetics, gammas
					2.00	2.67	2.40	
1	32 40.17	114 34.83	212.89	979508.66	−14.9	−16.7	−16.0	49330
2	32 40.20	114 34.95	211.72	979510.25	−13.4	−15.2	−14.5	49353
R257	32 40.17	114 34.83	214.47	979508.84	−14.6	−16.5	−15.7	49393
3	32 40.18	114 35.17	211.05	979514.60	−9.1	−10.9	−10.2	49390
4	32 40.18	114 35.37	210.42	979513.25	−10.5	−12.3	−11.6	49392
5	32 40.18	114 35.55	210.74	979514.15	−9.6	−11.4	−10.7	49403
6	32 40.18	114 35.72	212.93	979514.68	−8.9	−10.7	−10.0	49379
7	32 40.17	114 35.90	207.19	979515.07	−8.9	−10.7	−10.0	49235
8	32 40.18	114 36.08	195.81	979514.07	−10.7	−12.4	−11.7	49392
9	32 40.18	114 36.28	192.96	979513.52	−11.4	−13.1	−12.4	49341
10	32 40.18	114 36.45	191.49	979513.34	−11.7	−13.4	−12.7	49417
11	32 40.17	114 36.62	190.84	979512.99	−12.1	−13.7	−13.1	49407
12	32 40.17	114 36.77	192.88	979512.26	−12.7	−14.3	−13.7	49833
13	32 40.17	114 36.93	192.60	979512.62	−12.3	−14.0	−13.3	49388
14	32 40.12	114 36.88	193.32	979511.53	−13.3	−15.0	−14.3	49365
15	32 39.97	114 36.88	197.41	979511.31	−13.1	−14.7	−14.1	49391
16	32 39.80	114 36.88	191.74	979512.25	−12.3	−13.9	−13.2	49376
17	32 39.63	114 36.88	188.59	979512.86	−11.6	−13.3	−12.6	49379
19	32 39.30	114 36.90	187.02	979513.17	−11.0	−12.6	−11.9	49390
20	32 39.30	114 37.10	186.12	979512.82	−11.4	−13.0	−12.3	49379
21	32 39.30	114 37.28	186.01	979511.70	−12.5	−14.1	−13.5	49350
22	32 39.18	114 37.40	185.46	979511.34	−12.8	−14.4	−13.7	49336
23	32 39.03	114 37.40	186.82	979511.25	−12.6	−14.2	−13.5	49355
24	32 38.87	114 37.38	192.48	979509.81	−13.4	−15.0	−14.4	49331
25	32 38.68	114 37.40	202.08	979509.51	−13.8	−15.5	−14.8	49335
26	32 38.57	114 37.52	192.20	979509.31	−13.5	−15.1	−14.5	49328
27	32 38.45	114 37.67	185.23	979510.12	−13.0	−14.6	−13.9	49305
28	32 38.33	114 37.80	182.49	979510.88	−12.3	−13.8	−13.2	49326
29	32 38.22	114 37.93	178.91	979511.34	−11.9	−13.4	−12.8	49353
30	32 38.03	114 38.15	170.21	979511.60	−12.0	−13.4	−12.9	49380
31	32 37.87	114 38.20	163.63	979511.90	−11.9	−13.3	−12.7	49351
32	32 37.72	114 38.12	174.30	979510.89	−12.0	−13.5	−12.9	49351
33	32 37.55	114 37.97	188.68	979509.28	−12.4	−14.0	−13.3	49339
34	32 37.55	114 37.78	190.49	979508.46	−13.1	−14.7	−14.0	49313
35	32 37.55	114 37.60	192.53	979507.80	−13.6	−15.2	−14.6	49316
36	32 37.55	114 37.38	193.53	979507.25	−14.1	−15.7	−15.1	49310
37	32 37.73	114 37.38	194.91	979507.17	−14.3	−16.0	−15.3	49316
38	32 37.88	114 37.38	193.12	979507.43	−14.4	−16.0	−15.4	49305
39	32 38.10	114 37.40	193.47	979507.84	−14.2	−15.9	−15.2	49298

See footnotes at end of table.

TABLE A-4. (Contd.)

Station ID	Latitude[a]	Longitude[a]	Elevation, ft	Gravity,[b] mgal	Complete Bouguer anomalies,[c] g/cm³			Corrected magnetics, gammas
					2.00	2.67	2.40	
40	32 38.23	114 37.25	195.37	9795[illegible]7.47	−14.6	−16.3	−15.6	49308
41	32 38.35	114 37.12	199.67	979507.05	−14.9	−16.6	−16.0	49317
42	32 38.43	114 37.00	199.37	979507.08	−15.0	−16.7	−16.1	49315
43	32 38.42	114 36.78	198.29	979506.95	−15.2	−16.9	−16.2	49335
44	32 38.43	114 36.62	197.70	979506.66	−15.6	−17.3	−16.6	49331
45	32 38.42	114 36.62	197.49	979506.47	−15.8	−17.5	−16.8	49338
46	32 38.42	114 36.25	199.85	979506.17	−15.9	−17.6	−16.9	49339
47	32 38.42	114 36.03	201.66	979506.13	−15.8	−17.6	−16.9	49357
48	32 38.42	114 35.85	203.43	979506.14	−15.7	−17.4	−16.7	49363
49	32 38.42	114 35.65	203.51	979506.61	−15.2	−17.0	−16.3	49364
50	32 38.42	114 35.42	204.19	979507.07	−14.7	−16.5	−15.8	49376
51	32 38.42	114 35.25	203.91	979506.96	−14.8	−16.6	−15.9	49368
53	32 38.42	114 34.82	210.26	979503.86	−17.5	−19.3	−18.6	49342
54	32 38.57	114 34.82	206.27	979505.08	−16.8	−18.5	−17.8	49373
55	32 38.75	114 34.82	208.52	979506.78	−15.2	−16.9	−16.2	49379
56	32 38.92	114 34.82	208.87	979507.58	−14.6	−16.4	−15.6	49368
57	32 39.10	114 34.82	209.78	979508.42	−13.9	−15.7	−15.0	49365
58	32 39.28	114 34.83	209.05	979508.70	−13.9	−15.7	−15.0	49339
59	32 39.45	114 34.83	208.91	979508.68	−14.2	−16.0	−15.3	49349
60	32 39.62	114 34.83	210.47	979508.19	−14.8	−16.6	−15.9	49341
61	32 39.78	114 34.85	213.54	979507.89	−15.1	−16.9	−16.2	49404
62	32 40.02	114 34.85	211.15	979508.52	−15.0	−16.8	−16.1	49341
63	32 39.60	114 35.03	210.74	979511.46	−11.5	−13.3	−12.6	49562
64	32 39.43	114 35.02	207.75	979511.19	−11.7	−13.5	−12.8	49325
65	32 39.33	114 35.03	209.12	979511.50	−11.2	−13.0	−12.3	49116
66	32 39.33	114 35.27	226.85	979512.61	−8.9	−10.8	−10.0	49206
67	32 39.33	114 35.45	228.44	979512.96	−8.4	−10.4	−9.6	49328
68	32 39.22	114 35.57	221.73	979513.26	−8.4	−10.3	−9.5	49395
69	32 39.03	114 35.57	202.64	979511.37	−11.4	−13.1	−12.4	49408
70	32 38.92	114 35.63	198.70	979510.46	−12.4	−14.1	−13.4	49402
71	32 38.85	114 35.77	196.76	979509.81	−13.1	−14.8	−14.1	49405
72	32 38.85	114 35.97	194.24	979509.79	−13.3	−14.9	−14.3	49408
73	32 38.85	114 36.15	189.76	979509.67	−13.7	−15.3	−14.7	49400
74	32 38.87	114 36.35	189.88	979509.48	−13.9	−15.5	−14.9	49414
75	32 38.82	114 36.62	190.18	979509.29	−14.0	−15.6	−15.0	49417
76	32 38.70	114 36.75	193.09	979508.69	−14.2	−15.9	−15.2	49398
77	32 38.58	114 36.87	195.61	979508.04	−14.5	−16.2	−15.5	49378
78	32 38.45	114 37.00	200.50	979507.39	−14.7	−16.4	−15.7	49376
79	32 39.05	114 35.37	210.77	979511.78	−10.4	−12.2	−11.5	49400

See footnotes at end of table.

TABLE A-4. (Contd.)

Station ID	Latitude[a]	Longitude[a]	Elevation, ft	Gravity,[b] mgal	Complete Bouguer anomalies,[c] g/cm³			Corrected magnetics, gammas
					2.00	2.67	2.40	
80	32 39.03	114 35.22	212.97	979511.42	−10.6	−12.4	−11.7	49286
81	32 39.03	114 35.02	206.96	979510.02	−12.4	−14.2	−13.5	49299
82	32 39.05	114 34.83	209.13	979508.46	−13.8	−15.6	−14.9	49261
83	32 39.48	114 35.45	212.07	979511.92	−10.8	−12.6	−11.9	49300
84	32 39.60	114 35.45	210.26	979511.19	−11.8	−13.6	−12.9	49212
85	32 39.60	114 35.25	210.40	979511.22	−11.8	−13.6	−12.8	50117
86	32 39.62	114 35.07	211.34	979510.24	−12.7	−14.5	−13.8	49201
87	32 38.07	114 34.82	204.64	979502.16	−19.1	−20.9	−20.2	49331
88	32 37.73	114 34.80	200.16	979499.27	−21.9	−23.6	−22.9	49337
89	32 37.38	114 34.80	200.22	979496.72	−23.9	−25.6	−24.9	49315
90	32 37.03	114 34.80	206.05	979495.50	−24.3	−26.0	−25.3	49298
91	32 36.67	114 34.78	201.29	979495.49	−24.1	−25.8	−25.1	49282
92	32 36.35	114 34.80	199.80	979496.02	−23.2	−24.9	−24.2	49282
93	32 35.98	114 34.80	200.50	979497.30	−21.4	−23.1	−22.4	49269
94	32 35.65	114 34.78	200.41	979498.67	−19.6	−21.3	−20.6	49262
95	32 35.27	114 34.78	200.92	979499.80	−17.9	−19.6	−18.9	49260
96	31 40.32	113 49.53	204.47	979499.55	56.6	54.9	55.6	49270
97	32 34.58	114 34.78	197.78	979498.92	−18.1	−19.8	−19.1	49279
98	32 34.27	114 34.78	202.35	979496.06	−20.2	−21.9	−21.2	49277
99	32 33.87	114 34.77	204.56	979493.19	−22.3	−24.1	−23.4	49262
100	32 33.53	114 34.77	205.95	979491.23	−23.8	−25.5	−24.8	49243
101	32 33.18	114 34.78	207.48	979490.40	−24.0	−25.8	−25.1	49224
102	31 39.95	113 32.30	197.22	979492.12	49.2	47.5	48.2	49209
103	32 33.17	114 35.58	194.70	979492.95	−22.3	−24.0	−23.3	49211
104	32 33.17	114 36.00	192.55	979493.50	−21.9	−23.5	−22.9	48198
105	32 33.17	114 36.38	192.30	979493.78	−21.6	−23.3	−22.6	49185
106	32 33.17	114 36.83	193.10	979493.81	−21.5	−23.2	−22.5	49178
107	32 33.50	114 36.85	189.92	979494.83	−21.2	−22.8	−22.2	49197
108	32 33.82	114 36.85	190.70	979495.38	−21.0	−22.7	−22.0	49208
109	32 34.15	114 36.85	191.57	979496.42	−20.4	−22.0	−21.4	49219
110	32 34.55	114 36.85	193.73	979498.00	−19.2	−20.9	−20.2	49261
111	32 34.88	114 36.85	195.05	979500.30	−17.3	−18.9	−18.3	49301
112	32 35.27	114 36.85	196.51	979504.22	−13.8	−15.5	−14.8	49400
113	32 35.62	114 36.87	197.51	979508.32	−10.1	−11.8	−11.1	49364
114	32 35.95	114 36.87	194.18	979510.39	−8.7	−10.4	−9.7	49332
115	32 36.28	114 36.87	194.92	979509.12	−10.4	−12.0	−11.4	49313
116	32 36.68	114 36.87	198.34	979506.78	−13.0	−14.7	−14.0	49320
117	32 37.02	114 36.87	193.02	979506.03	−14.6	−16.2	−15.6	49324
118	32 37.28	114 36.87	192.48	979502.92	−18.1	−19.8	−19.1	49307
119	32 37.63	114 36.87	191.89	979505.82	−15.7	−17.4	−16.7	49306

See footnotes at end of table.

TABLE A-4. (Contd.)

Station ID	Latitude[a]	Longitude[a]	Elevation, ft	Gravity,[b] mgal	Complete Bouguer anomalies,[c] g/cm³			Corrected magnetics, gammas
					2.00	2.67	2.40	
120	32 37.93	114 36.87	194.09	979505.93	−15.9	−17.5	−16.9	49304
121	32 38.27	114 36.87	195.63	979506.52	−15.6	−17.3	−16.6	49319
122	32 33.17	114 34.30	219.60	979487.52	−26.0	−27.9	−27.1	49245
123	32 33.17	114 33.90	216.55	979486.65	−27.1	−29.0	−28.2	49245
124	32 33.38	114 33.73	212.55	979486.80	−27.5	−29.3	−28.6	49262
125	32 33.70	114 33.73	230.12	979486.71	−26.8	−28.8	−28.0	49275
126	32 34.05	114 33.75	207.81	979489.77	−25.8	−27.6	−26.8	49263
127	32 34.37	114 33.75	197.99	979491.36	−25.3	−27.0	−26.3	49267
128	32 34.67	114 33.75	199.28	979491.47	−25.5	−27.2	−26.5	49267
129	32 34.67	114 33.37	203.36	979487.86	−28.9	−30.6	−29.9	49239
130	32 34.85	114 33.22	205.32	979486.65	−30.2	−31.9	−31.2	49234
131	32 35.20	114 33.22	200.44	979487.19	−30.4	−32.2	−31.5	49229
132	32 35.53	114 33.20	201.88	979487.26	−30.7	−32.5	−31.8	49230
133	32 35.82	114 33.12	205.62	979486.42	−31.7	−33.5	−32.8	49218
134	32 35.83	114 32.73	205.02	979484.33	−33.8	−35.6	−34.9	49222
135	32 33.17	114 33.48	213.30	979484.68	−29.3	−31.1	−30.4	49237
136	32 33.15	114 33.28	223.91	979482.64	−30.6	−32.5	−31.7	49233
137	32 33.15	114 33.10	230.99	979481.05	−31.7	−33.7	−32.9	49235
138	32 33.15	114 32.92	242.60	979479.19	−32.8	−34.8	−34.0	49237
139	32 33.17	114 32.65	239.70	979477.86	−34.3	−36.3	−35.5	49229
140	32 33.17	114 32.43	235.47	979477.22	−35.2	−37.2	−36.4	49220
141	32 33.17	114 32.25	235.01	979476.36	−36.1	−38.1	−37.3	49223
142	32 33.17	114 32.05	234.32	979475.65	−36.9	−38.9	−38.1	49218
143	32 33.17	114 31.83	236.92	979474.61	−37.7	−39.8	−38.9	49219
144	32 33.17	114 31.60	239.96	979473.64	−38.5	−40.6	−39.7	49216
145	32 33.17	114 31.42	243.77	979472.70	−39.2	−41.3	−40.4	49217
146	32 33.17	114 31.22	247.41	979471.94	−39.7	−41.8	−41.0	49220
147	32 33.05	114 31.03	250.80	979471.18	−40.1	−42.2	−41.4	49212
148	32 33.02	114 30.88	254.11	979470.44	−40.5	−42.7	−41.8	49263
149	32 33.02	114 30.68	256.45	979469.83	−41.0	−43.2	−42.3	49199
150	32 33.02	114 30.50	258.77	979469.20	−41.5	−43.7	−42.8	49213
151	32 32.98	114 30.35	262.76	979468.64	−41.7	−43.9	−43.0	48207
152	32 32.80	114 30.48	259.83	979469.16	−41.1	−43.4	−42.5	49195
153	32 32.67	114 30.57	254.40	979469.73	−40.7	−42.9	−42.0	49209
154	32 32.52	114 30.68	253.76	979470.01	−40.3	−42.5	−41.6	49199
155	32 32.32	114 30.58	260.11	979469.32	−40.3	−42.5	−41.6	49209
156	32 32.15	114 30.52	264.72	979468.97	−40.1	−42.4	−41.4	49204
157	32 32.00	114 30.45	269.08	979468.44	−40.1	−42.4	−41.5	49206
158	32 31.83	114 30.38	270.65	979468.20	−40.0	−42.3	−41.4	49204
159	32 31.63	114 30.30	277.57	979467.43	−40.1	−42.4	−41.5	49195

See footnotes at end of table.

TABLE A-4. (Contd.)

Station ID	Latitude[a]	Longitude[a]	Elevation, ft	Gravity,[b] mgal	Complete Bouguer anomalies,[c] g/cm³			Corrected magnetics, gammas
					2.00	2.67	2.40	
160	32 31.48	114 30.23	277.39	979467.41	−39.9	−42.3	−41.3	49197
161	32 31.33	114 30.17	277.61	979467.19	−39.9	−42.3	−41.3	49194
162	32 31.18	114 30.10	276.79	979467.12	−39.8	−42.2	−41.2	49192
163	32 30.98	114 30.02	279.82	979466.79	−39.7	−42.0	−41.1	49189
164	32 30.83	114 29.95	280.08	979466.62	−39.6	−42.0	−41.0	49187
165	32 30.67	114 29.88	281.16	979466.40	−39.5	−41.9	−41.0	49183
166	32 30.55	114 29.85	282.76	979466.24	−39.4	−41.8	−40.9	49167
167	32 30.55	114 30.05	276.79	979466.94	−39.1	−41.5	−40.5	49169
168	32 30.55	114 30.27	272.70	979467.68	−38.7	−41.0	−40.0	49171
169	32 30.55	114 30.45	267.79	979468.32	−38.3	−40.6	−39.7	49174
170	32 30.55	114 30.65	264.04	979469.02	−37.9	−40.2	−39.3	49174
171	32 30.55	114 30.88	260.11	979469.87	−37.3	−39.6	−38.7	49178
172	32 30.55	114 31.10	256.53	979470.96	−36.5	−38.7	−37.8	49176
173	32 30.55	114 31.30	257.45	979471.55	−35.8	−38.0	−37.1	49181
174	32 30.55	114 31.50	267.13	979471.62	−35.1	−37.4	−36.5	49182
175	32 30.55	114 31.73	280.29	979471.63	−34.2	−36.6	−35.6	49182
176	32 30.55	114 31.92	274.95	979472.86	−33.3	−35.7	−34.7	49180
177	32 30.55	114 32.12	287.41	979472.50	−32.8	−35.3	−34.3	49170
178	32 30.07	114 32.30	299.59	979472.31	−31.5	−34.1	−33.0	49178
179	32 30.55	114 32.57	303.00	979472.76	−31.5	−34.1	−33.1	49175
180	32 30.55	114 32.78	302.70	979473.40	−30.9	−33.5	−32.4	49174
181	32 30.55	114 32.98	299.85	979473.89	−30.6	−33.2	−32.1	49174
182	32 30.57	114 33.17	299.93	979474.12	−30.4	−32.9	−31.9	49176
183	32 30.55	114 33.42	292.93	979474.84	−30.1	−32.6	−31.6	49166
184	32 30.55	114 33.70	286.08	979475.78	−29.6	−32.1	−31.1	49169
185	32 30.72	114 33.73	288.14	979476.07	−29.4	−31.9	−30.9	49186
186	32 30.88	114 33.72	294.63	979476.05	−29.2	−31.8	−30.7	49180
187	32 31.05	114 33.72	295.64	979476.31	−29.1	−31.7	−30.7	49183
188	32 31.27	114 33.70	296.53	979476.65	−29.0	−31.6	−30.5	49177
189	32 31.42	114 33.72	299.63	979476.83	−28.9	−31.4	−30.4	49183
190	32 31.58	114 33.72	293.99	979477.64	−28.7	−31.2	−30.2	49193
191	32 31.73	114 33.72	293.52	979478.12	−28.4	−30.9	−29.9	49187
192	32 31.92	114 33.72	293.22	979478.51	−28.3	−30.8	−29.8	49194
193	32 32.15	114 33.72	297.65	979478.72	−28.1	−30.6	−29.6	49184
194	32 32.33	114 33.72	294.85	979479.21	−28.0	−30.6	−29.5	49186
195	32 32.48	114 33.72	282.44	979480.14	−28.2	−30.6	−29.6	49188
196	32 32.70	114 33.72	251.93	979482.93	−27.8	−29.9	−29.0	49199
197	32 32.87	114 33.73	229.46	979484.83	−27.6	−29.6	−28.8	49208
198	32 33.03	114 33.73	220.07	979485.67	−27.7	−29.5	−28.8	49214
199	32 33.17	114 30.95	251.58	979470.91	−40.4	−42.6	−41.7	49222

See footnotes at end of table.

TABLE A-4. (Contd.)

Station ID	Latitude[a]	Longitude[a]	Elevation, ft	Gravity,[b] mgal	Complete Bouguer anomalies,[c] g/cm³			Corrected magnetics, gammas
					2.00	2.67	2.40	
200	32 33.17	114 30.73	265.85	979469.94	-40.4	-42.7	-41.8	49225
201	32 33.32	114 30.67	260.32	979469.47	-41.5	-43.7	-42.8	49228
202	32 33.50	114 30.67	259.86	979469.52	-41.7	-43.9	-43.0	49229
203	32 33.67	114 30.70	260.13	979469.68	-41.8	-44.0	-43.1	49230
204	32 33.82	114 30.68	272.31	979468.87	-42.0	-44.3	-43.3	49231
205	32 33.97	114 30.72	280.31	979468.59	-41.9	-44.3	-43.3	49235
206	32 34.13	114 30.73	287.62	979468.16	-42.0	- 44.5	-43.5	49235
207	32 34.30	114 30.73	291.27	979468.19	-42.0	-44.5	-43.5	49235
208	32 34.45	114 30.77	292.16	799468.25	-42.1	-44.6	-43.6	49232
209	32 34.62	114 30.77	292.04	979468.34	-42.2	-44.7	-43.7	49292
210	32 34.77	114 30.78	287.80	979468.83	-42.2	-44.7	-43.7	49227
211	32 34.95	114 30.78	291.71	979468.61	-42.4	-44.9	-43.9	49220
212	32 35.12	114 30.78	296.27	979468.21	-42.7	-45.3	-44.3	49228
213	32 35.28	114 30.80	299.31	979468.19	-42.8	-45.4	-44.3	49227
214	32 35.45	114 30.75	283.56	979469.04	-43.2	-45.7	-44.7	49219
215	32 35.63	114 30.72	257.95	979470.80	-43.5	-45.7	-44.8	49223
216	32 35.78	114 30.68	254.98	979470.81	-43.9	-46.1	-45.2	49204
217	32 35.92	114 30.85	247.59	979471.87	-43.5	-45.6	-44.8	49205
218	32 35.98	114 31.07	243.35	979473.04	-42.7	-44.8	-44.0	49201
219	32 36.00	114 31.25	249.80	979473.42	-41.9	-44.1	-43.2	49200
220	32 36.02	114 31.42	259.17	979473.65	-41.1	-43.3	-42.4	49201
221	32 36.07	114 31.58	256.17	979474.55	-40.5	-42.7	-41.8	49206
222	32 35.95	114 31.67	228.86	979476.81	-39.9	-41.9	-41.1	49202
223	32 35.83	114 31.78	219.49	979577.99	-39.2	-41.1	-40.3	49195
224	32 35.88	114 31.97	209.59	979479.49	-38.5	-40.3	-39.5	49211
225	32 35 85	114 32.17	210.15	979480.48	-37.4	-39.2	-38.5	49197
226	32 35.83	114 32.38	199.33	979482.59	-36.0	-37.7	-37.0	49195
227	32 35.82	114 32.55	197.44	979483.58	-35.1	-36.8	-36.1	49200
228	32 38.42	114 34.38	204.37	979500.55	-21.2	-23.0	-22.3	49336
229	32 38.42	114 34.00	202.82	979497.23	-24.6	-26.4	-25.7	49292
230	32 38.43	114 33.57	205.07	979492.83	-28.9	-30.7	-29.9	49266
231	32 38.43	114 33.18	205.34	979489.44	-32.3	-34.0	-33.3	49252
232	32 38.43	114 32.77	208.86	979487.12	-34.4	-36.1	-35.4	49239
233	32 38.12	114 32.75	208.20	979485.35	-35.7	-37.5	-36.8	49244
234	32 37.77	114 32.75	206.09	979484.91	-35.8	-37.6	-36.9	49241
235	32 37.45	114 32.75	204.41	979484.80	-35.6	-37.4	-36.7	49226
236	32 37.07	114 32.75	203.58	979484.57	-35.4	-37.2	-36.5	49236
237	32 36.75	114 32.73	207.81	979484.05	-35.2	-37.0	-36.3	49240
238	32 36.37	114 32.73	202.10	979484.52	-34.6	-36.3	-35.6	49234
239	32 36.02	114 32.73	199.72	979484.58	-34.2	-35.9	-35.3	49231

See footnotes at end of table.

TABLE A-4. (Contd.)

Station ID	Latitude[a]	Longitude[a]	Elevation, ft	Gravity,[b] mgal	Complete Bouguer anomalies,[c] g/cm³			Corrected magnetics, gammas
					2.00	2.67	2.40	
240	32 31.87	114 33.50	286.64	979478.03	-29.1	-31.6	-30.6	49179
241	32 31.87	114 33.37	292.35	979477.13	-29.7	-32.2	-31.2	49187
242	32 31.83	114 33.20	294.65	979476.24	-30.3	-32.9	-31.9	49184
243	32 31.78	114 33.02	301.61	979474.91	-31.1	-33.7	-32.7	49190
244	32 31.82	114 32.83	296.20	979474.46	-32.0	-34.5	-33.5	49193
245	32 31.85	114 32.62	247.52	979477.17	-32.7	-34.8	-33.9	49195
246	32 31.85	114 32.45	242.57	979476.47	-33.7	-35.8	-34.9	49191
247	32 31.82	114 32.27	238.23	979475.98	-34.4	-36.5	-35.7	49193
248	32 31.80	114 32.07	238.13	979475.05	-35.4	-37.4	-36.6	49184
249	32 31.78	114 31.88	238.92	979474.35	-36.0	-38.0	-37.2	49182
250	32 31.77	114 31.70	240.79	979473.44	-36.7	-38.8	-38.0	49181

[a] Latitude and longitude from state-plane coordinates, AZ Zone WE.
[b] Drift-corrected observed gravity.
[c] Bouguer anomalies use post-1967 formula for latitude corrections.